NOvA's Capabilities to Measure Cross Section at the Resonance Region

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(on behalf on NOvA Collaboration)

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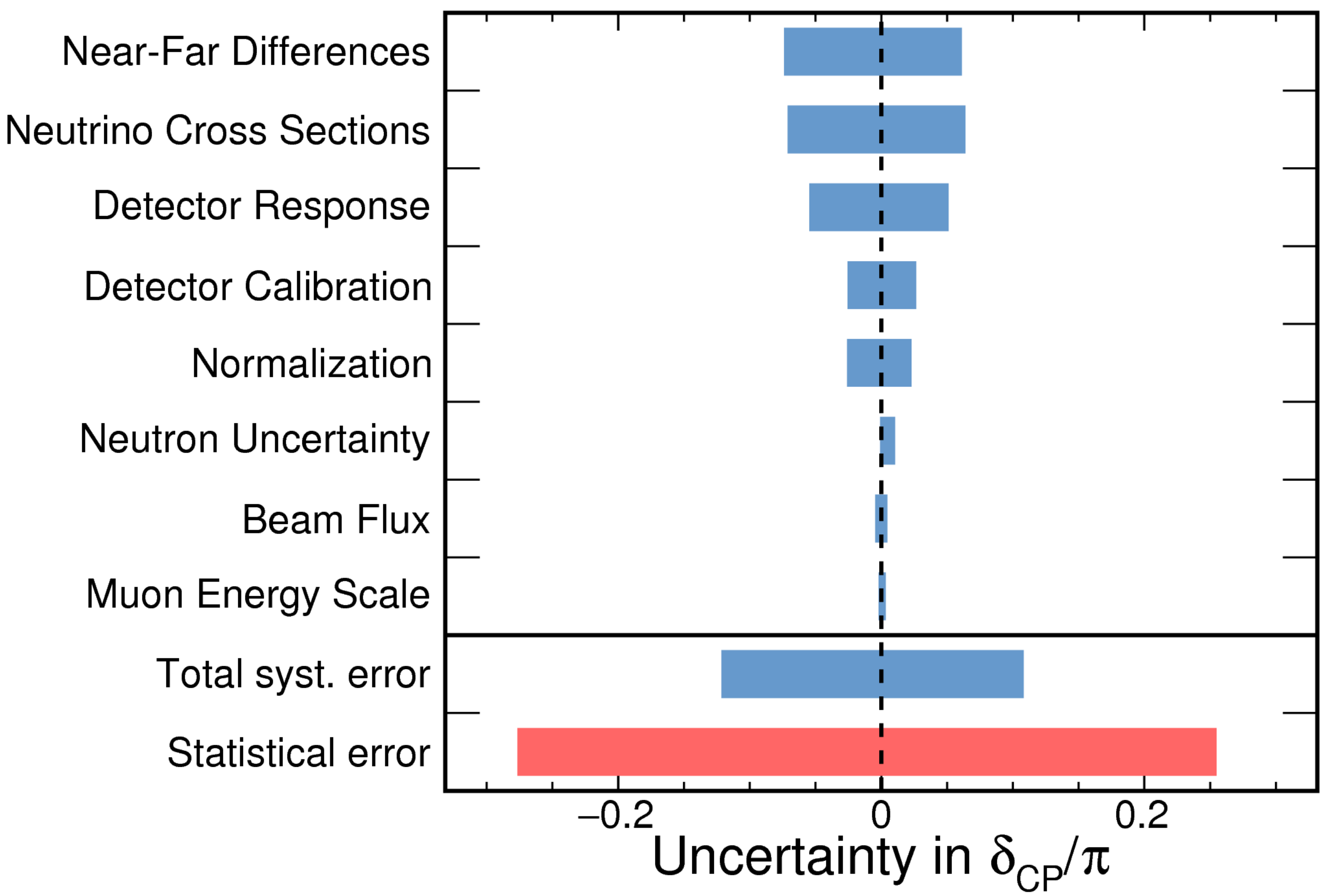
Neutrino-Nucleus Pion Production in the Resonance Region

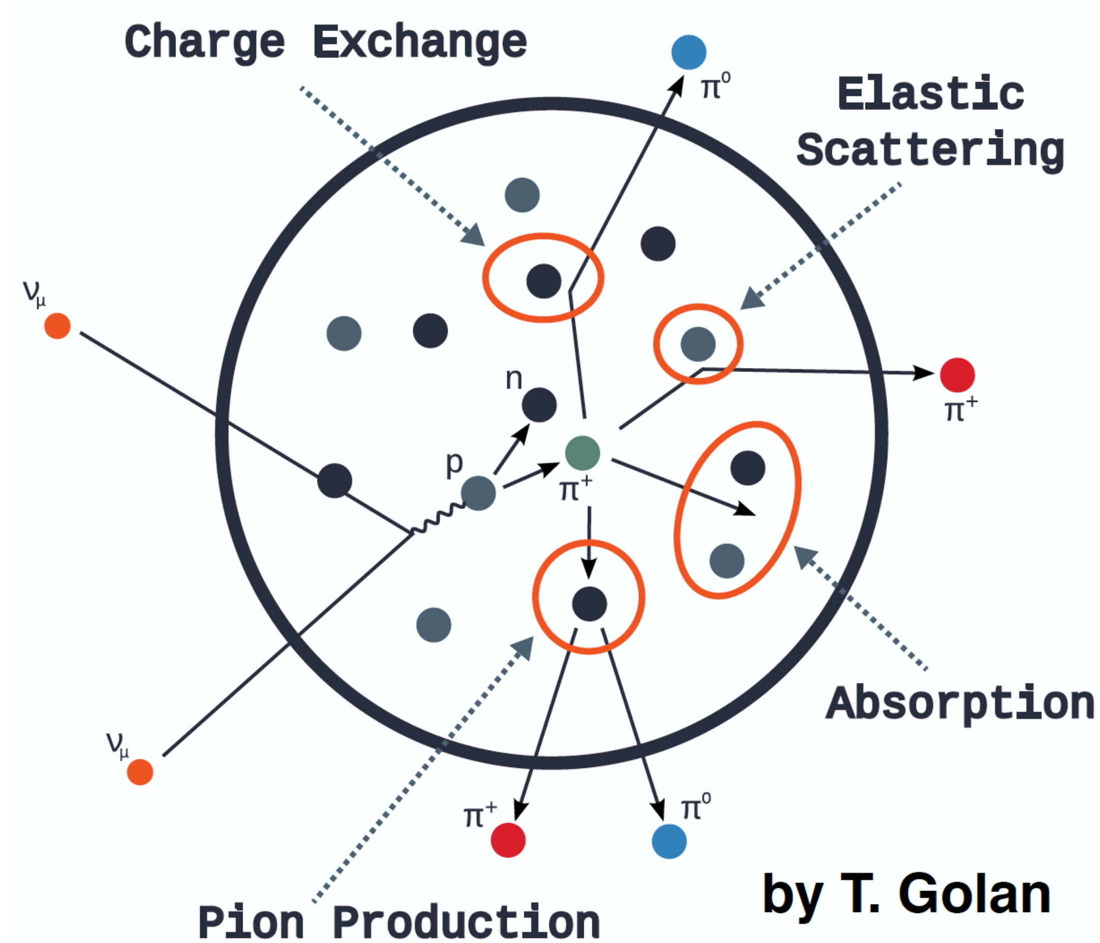
Introduction

- This talk summarizes the status of the cross-section program at the NOvA near detector.
- It is focused on detector capabilities and strategies we are following in our analyses to measure cross sections.
- This talk is structured showing the analyses lined up with the development and understanding of new tools that improve our measurements.

Motivation

- Cross-sections are rich in **physics themselves**.
- Also important to **oscillation systematic uncertainties**:
  - All channels are **signals** and **backgrounds** to the oscillation analysis.
  - Many of our measurements are sensitive to **nuclear effects** (fermi motion, nucleon correlation, final-state interaction…).

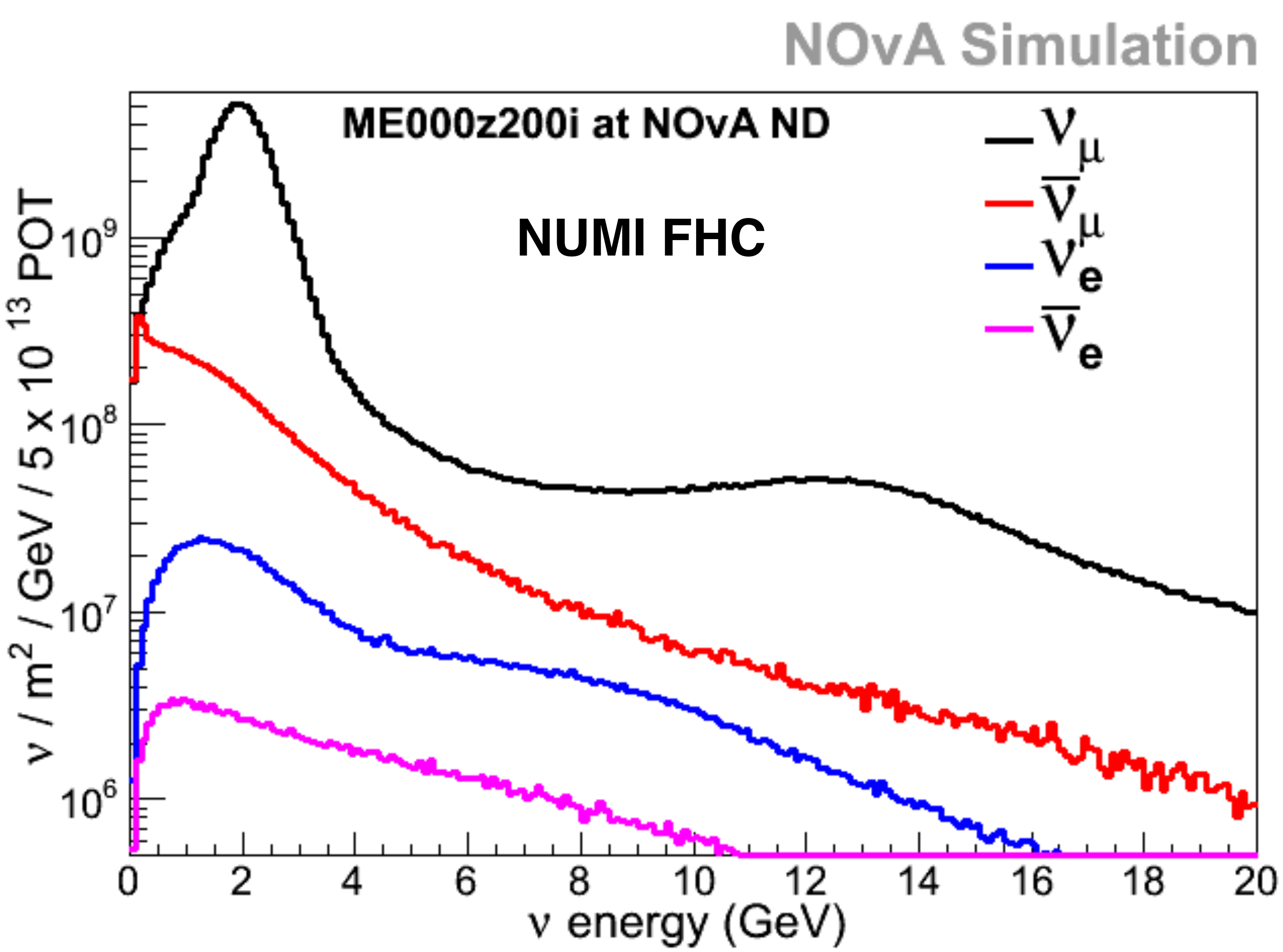


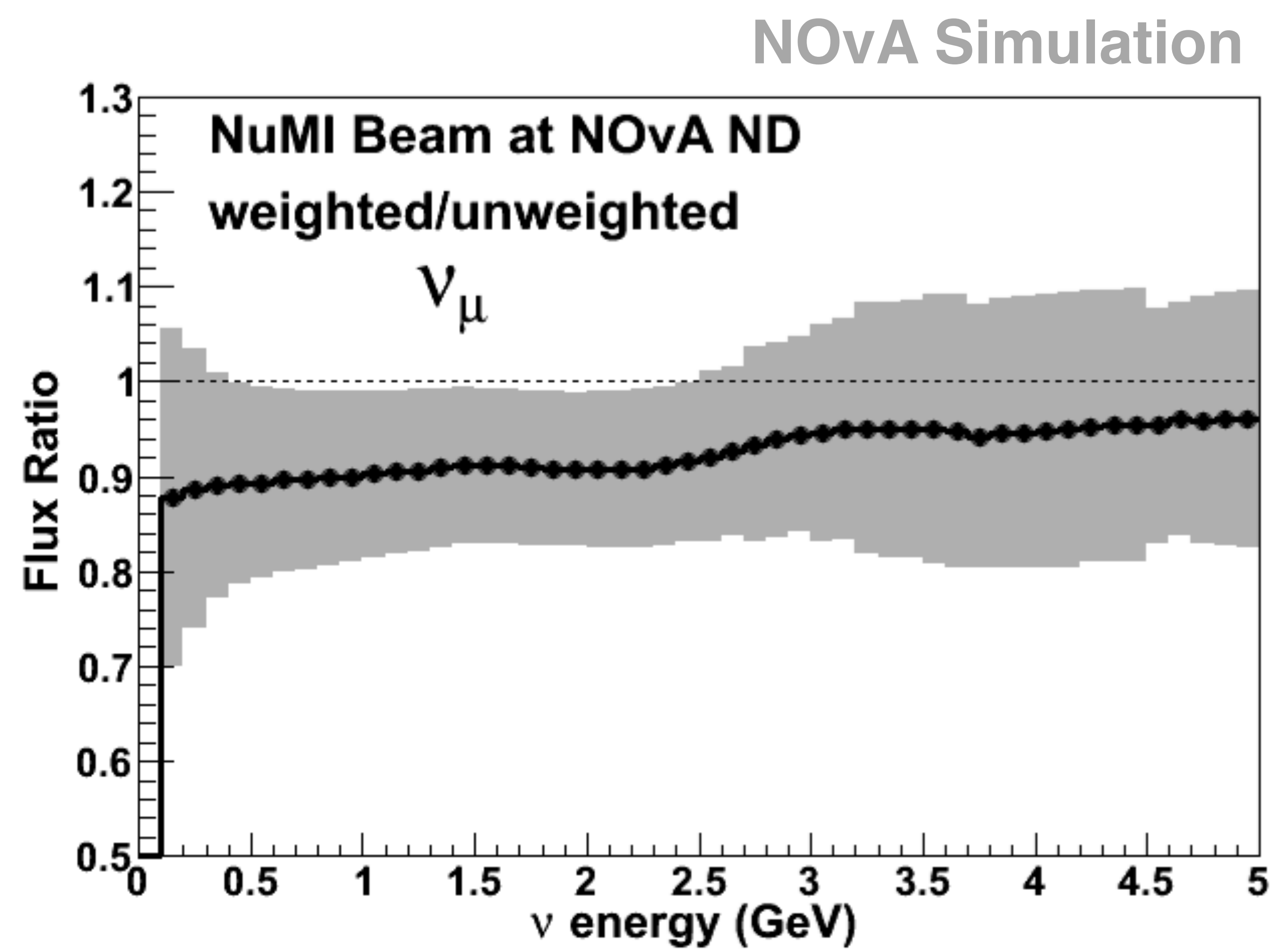


We want to understand those issues in our own detector

NuMI Beam at NOvA ND

- NOvA detectors are off-axis, **14 mrad** w.r.t NuMI beam axis.
  - It is a narrow-band beam centered around **2GeV**, right on the 1st DUNE oscillation maximum.
  - Both neutrino mode and anti-neutrino mode
  - Hadron production uncertainty constraint by external hadron production data.





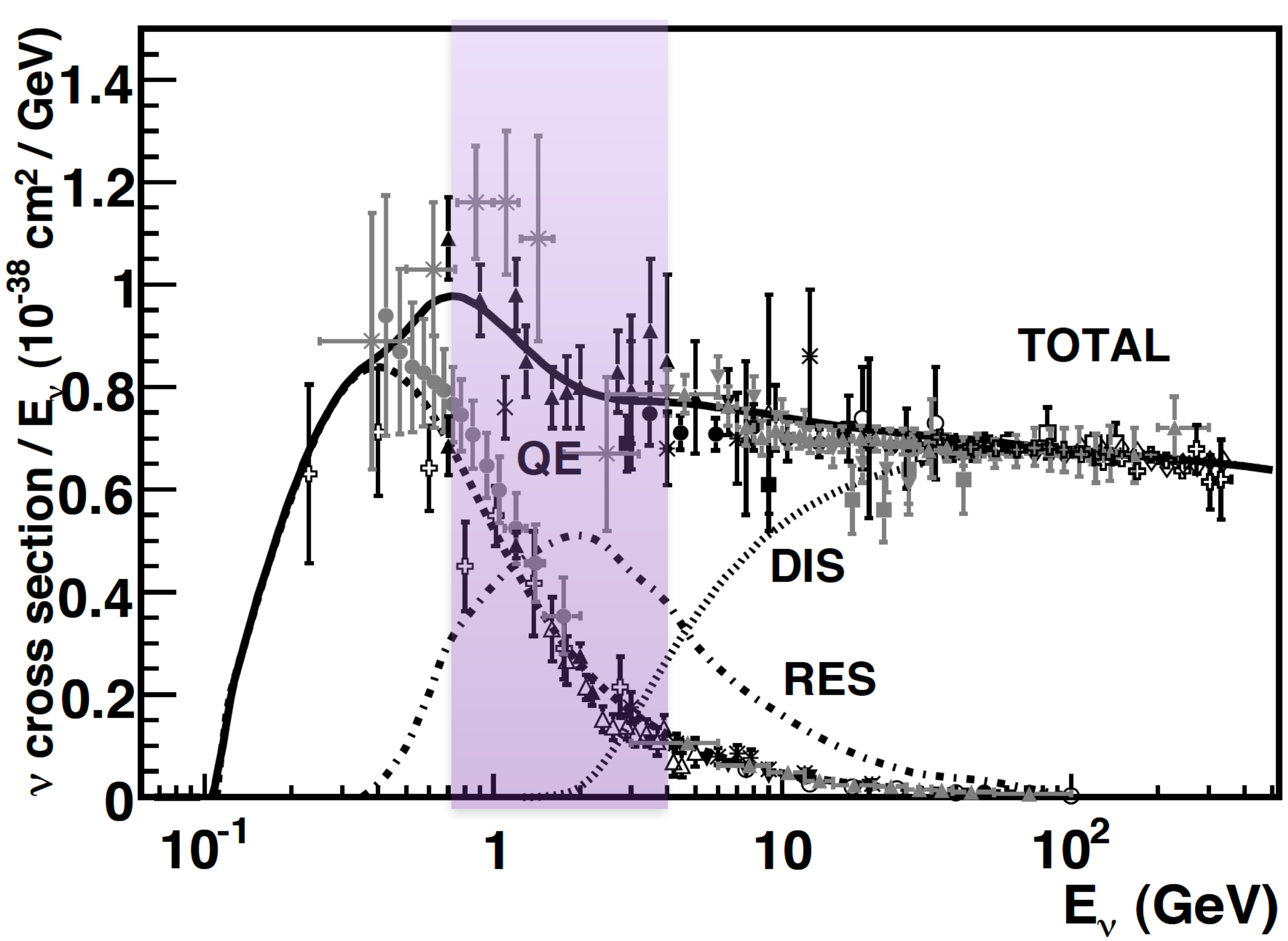
Event Rates at NOvA ND

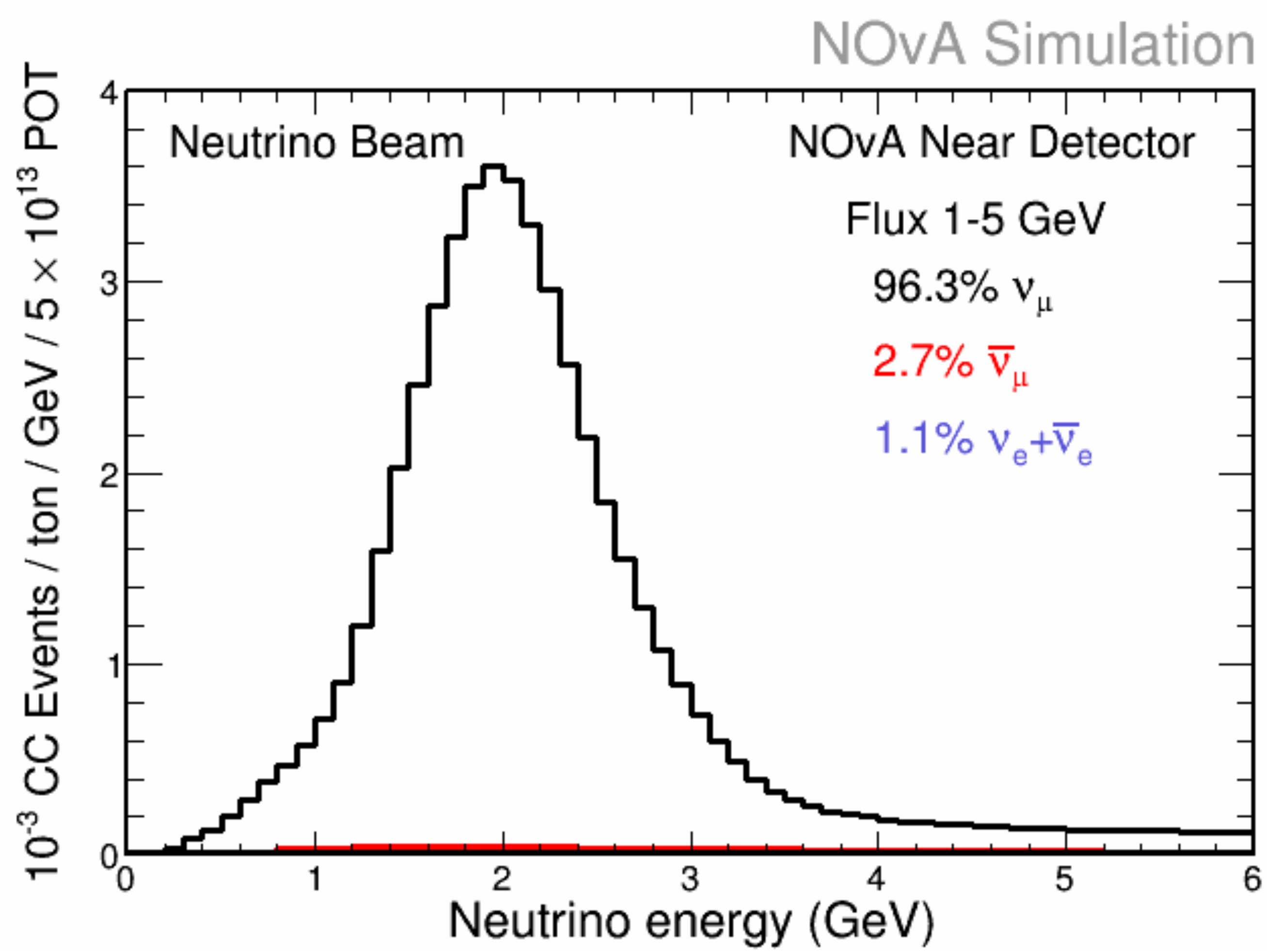
Protons on target

- FHC ~ **12 x 10^{20}**
- RHC ~ **12 x 10^{20}**

Even with a narrow band beam, NOvA is still sensitive to many different nu+A channels.

High data rate at the ND (~10^6 interactions in the whole data taking period).





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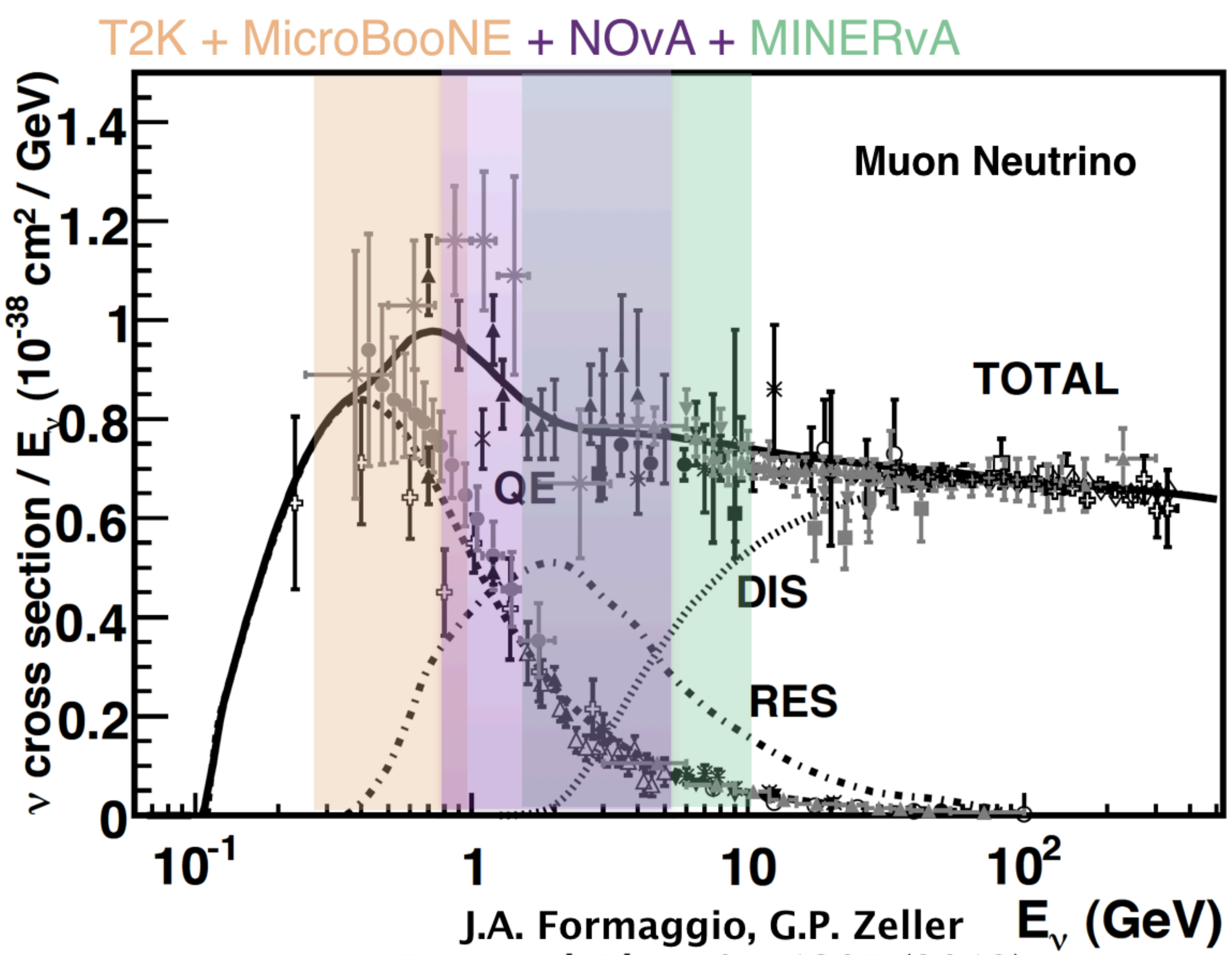
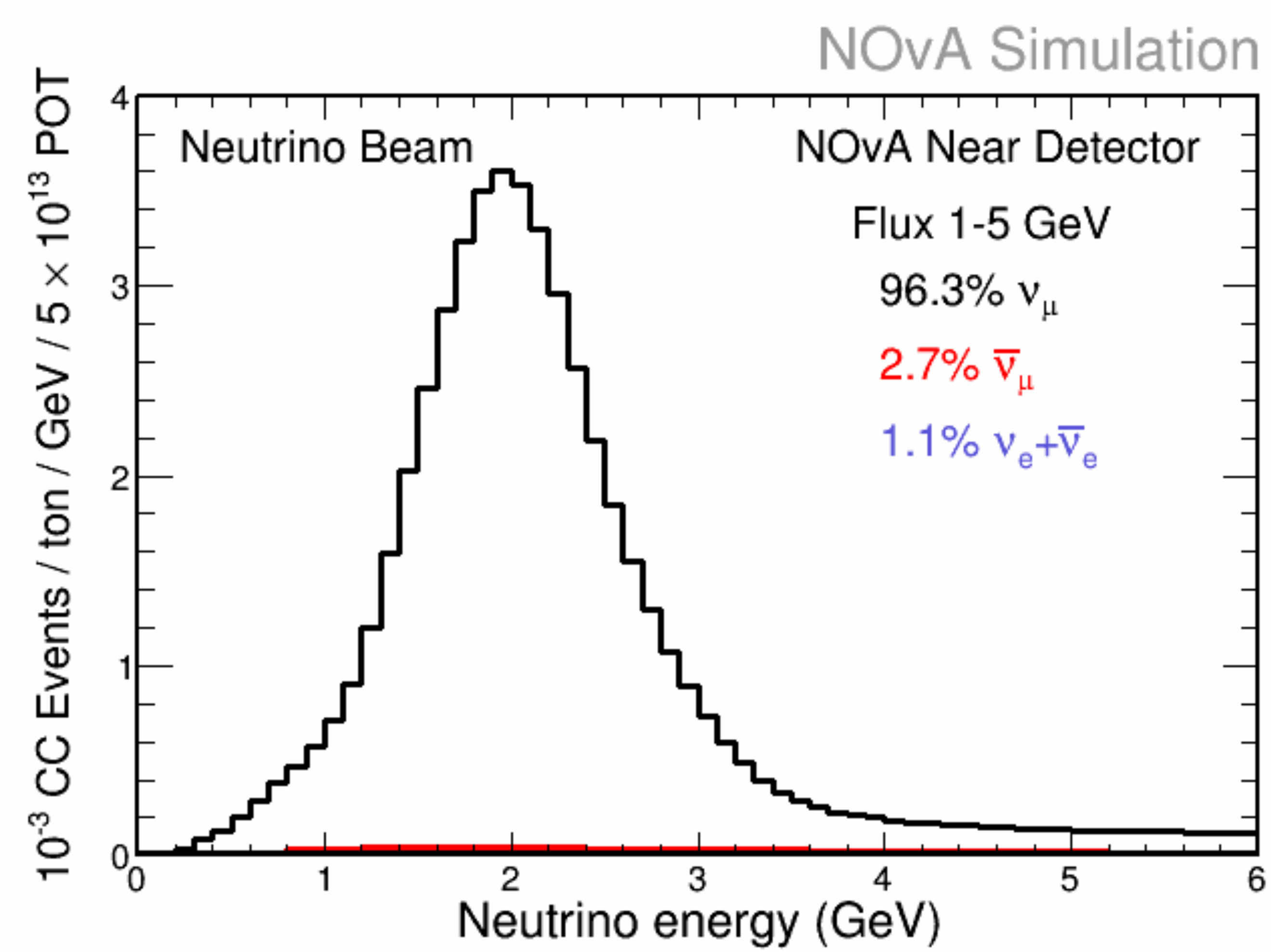


J.A. Formaggio, G.P. Zeller
Rev. Mod. Phys. 84, 1307 (2012)



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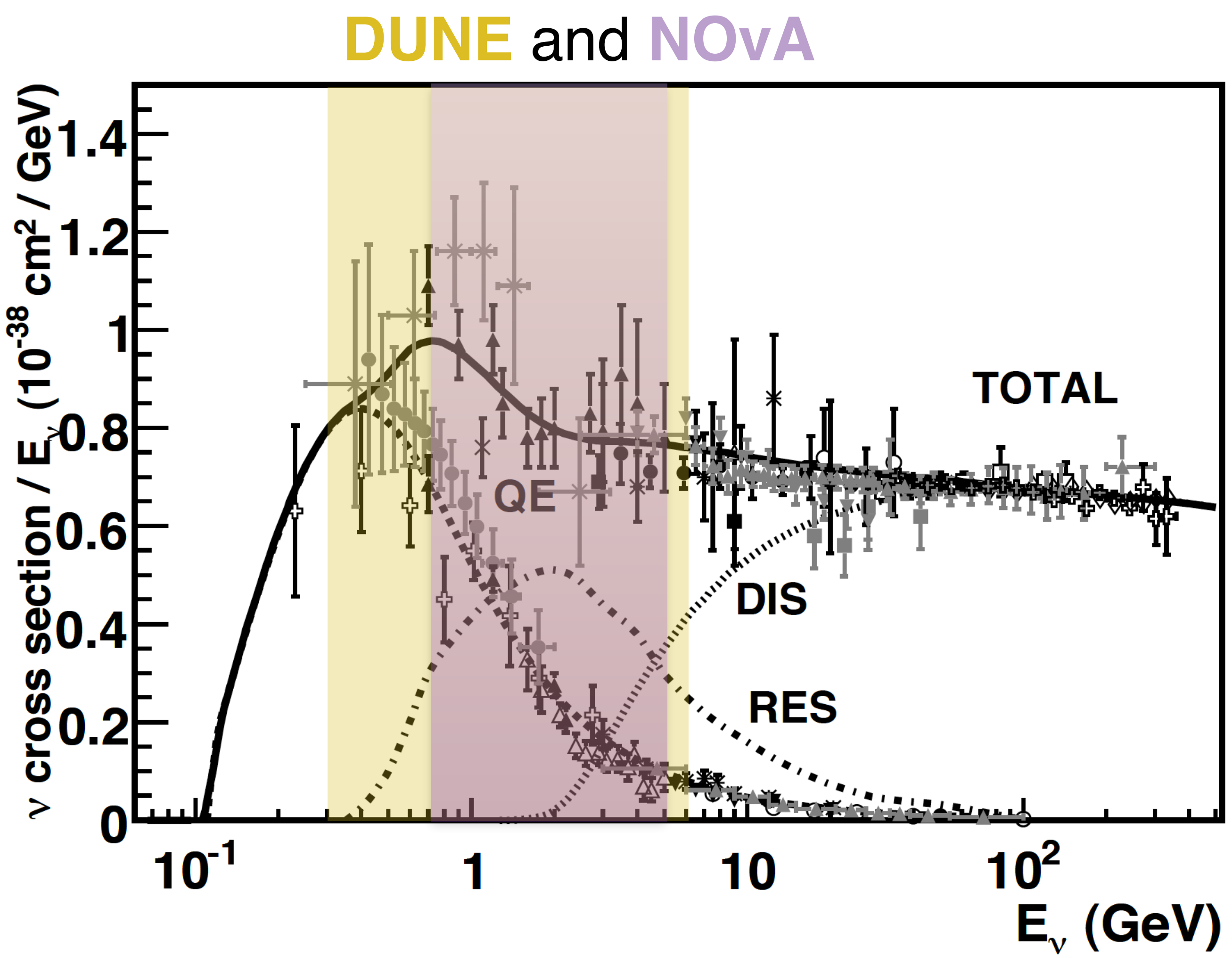
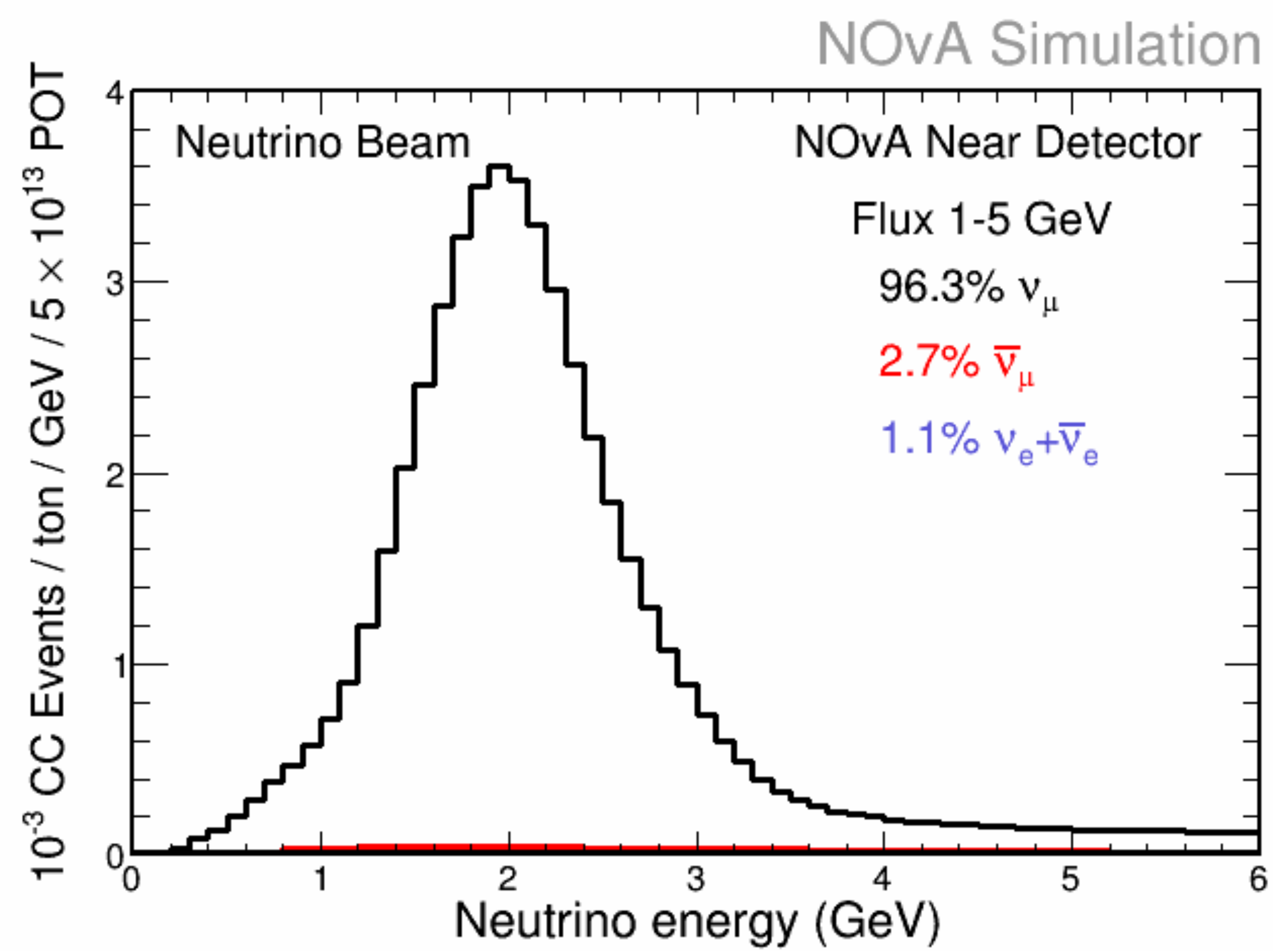




The NOvA Near Detector

The ND is **1 km** from source, **underground** at Fermilab.

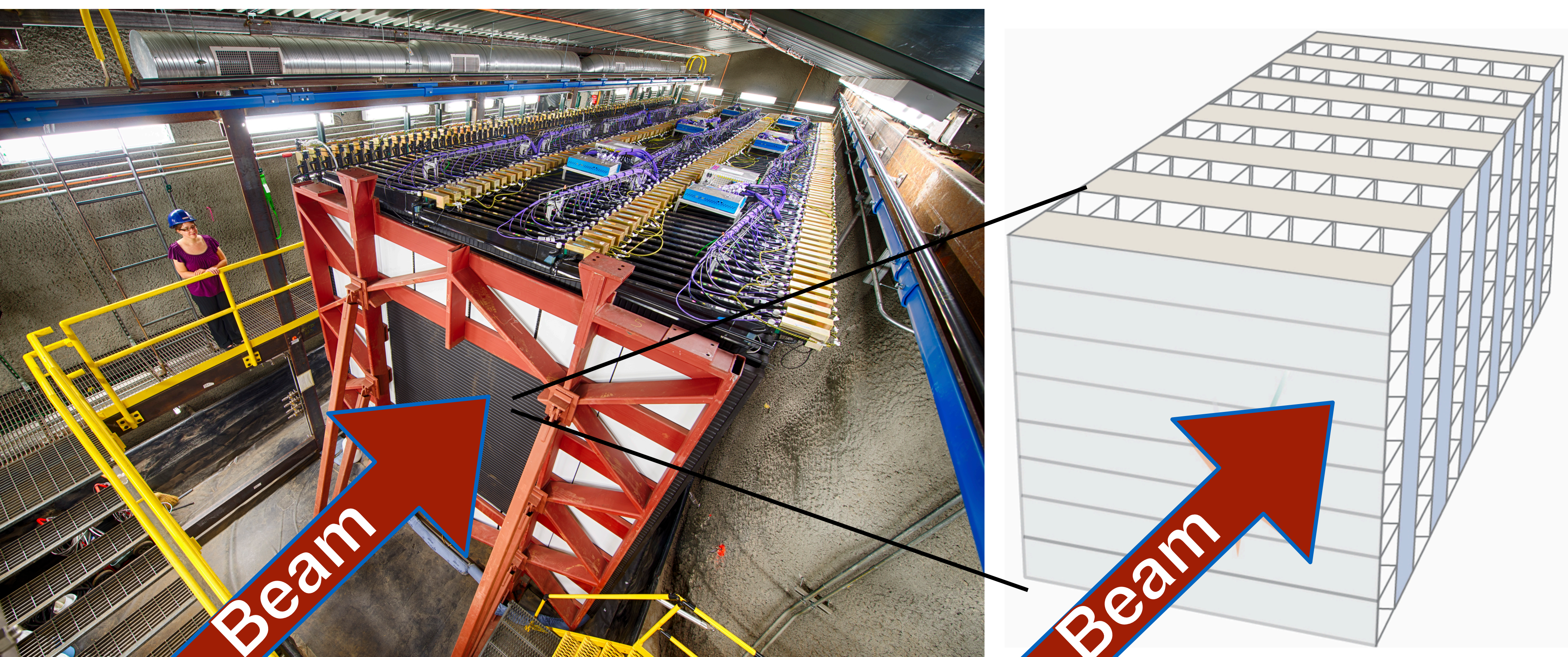
- PVC cells filled with **liquid scintillator, 193 ton** fully active mass and 97 ton downstream muon catcher.

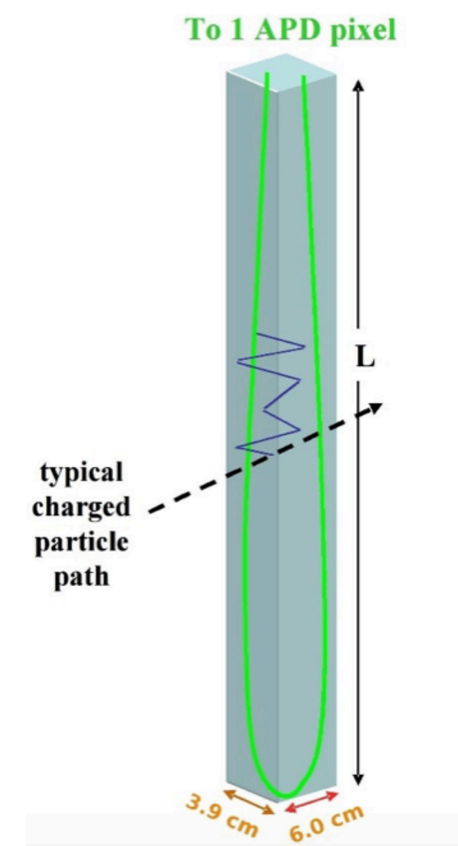
- Alternating planes of orthogonal views.

Low-Z, fine-grained:
1 plane ~$0.15X_0$ (38 cm)

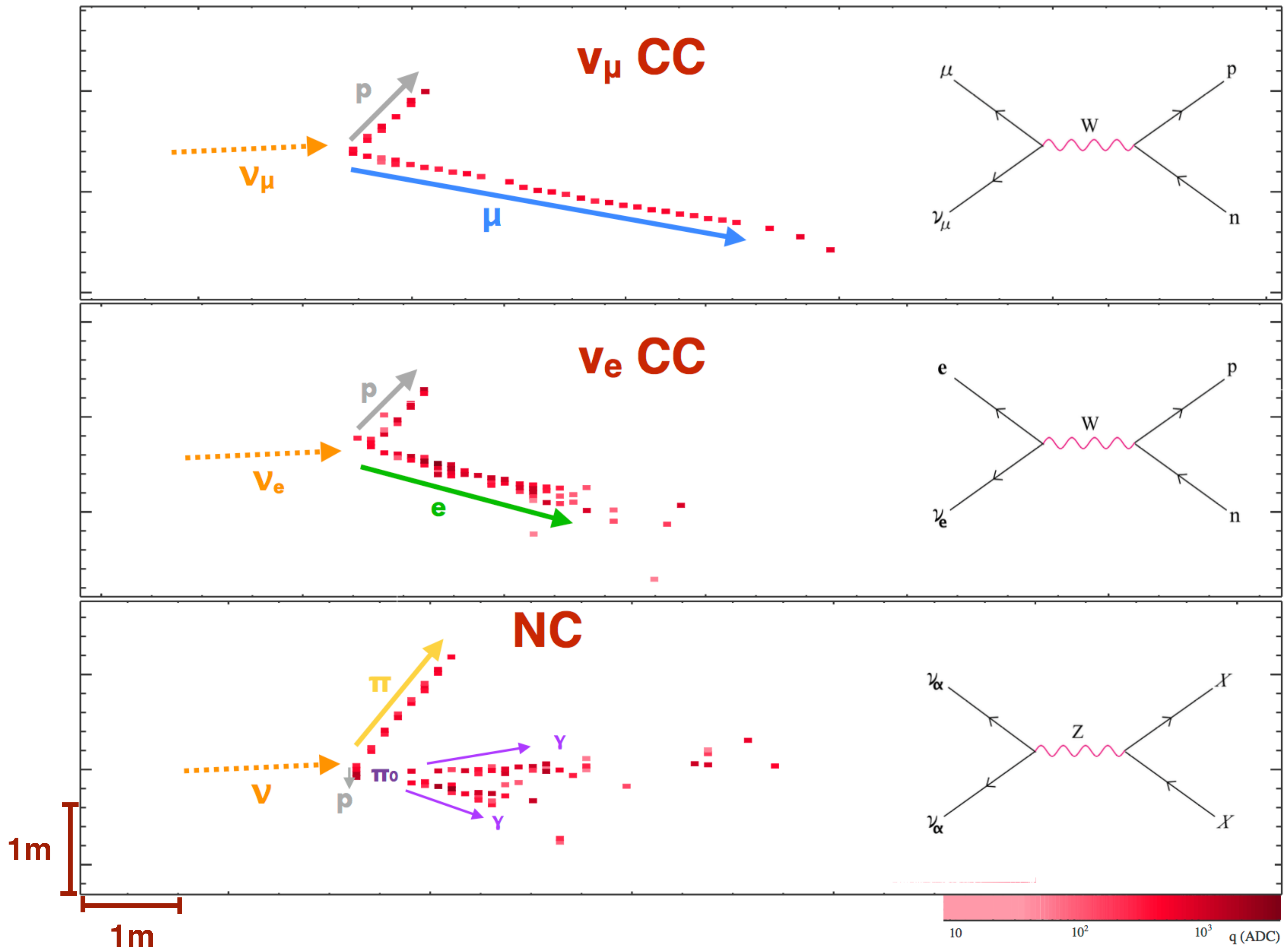
Percentage of total detector mass

C	Cl	H	O	Ti
65.9%	16.1%	10.7%	3.0%	2.4%



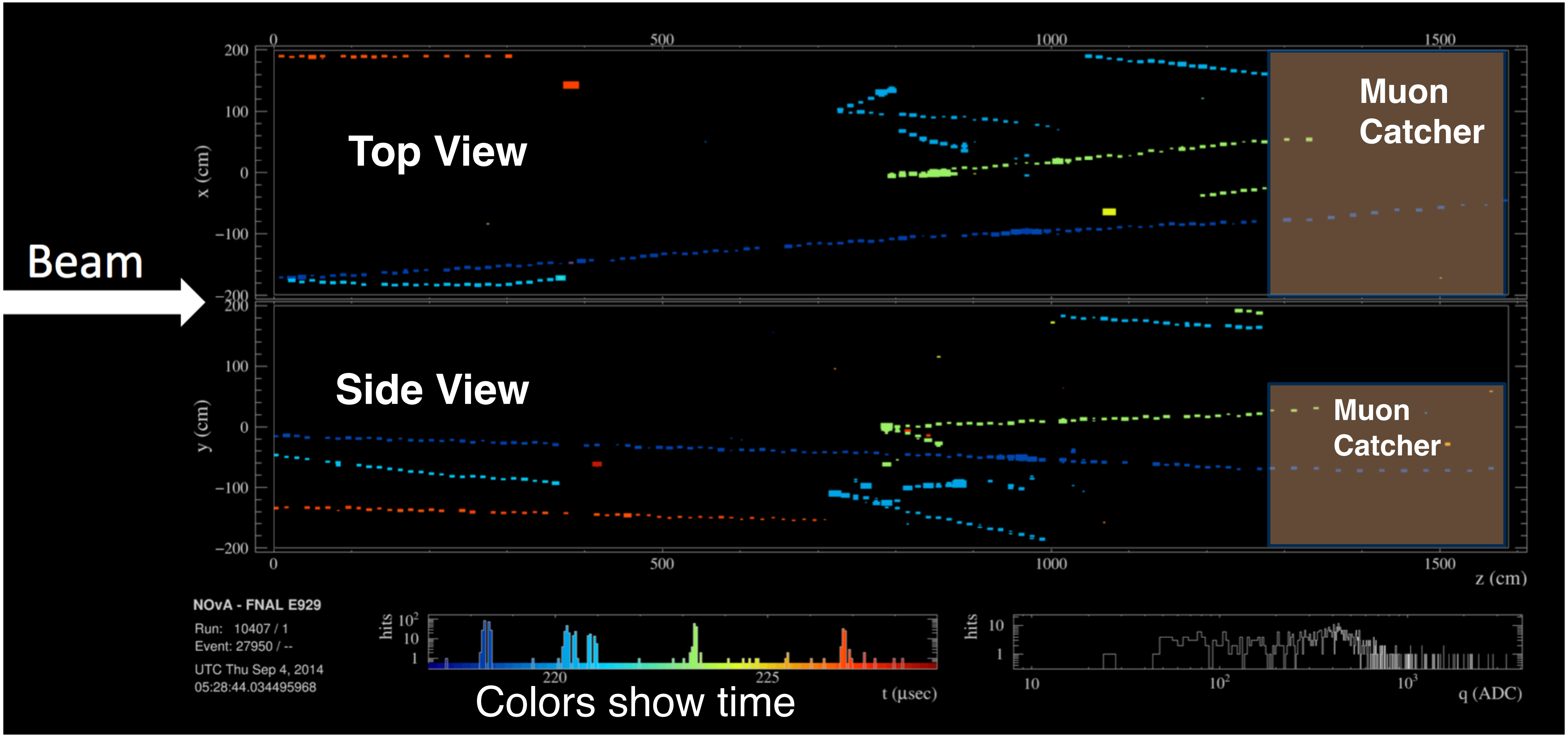


Examples of Event topologies



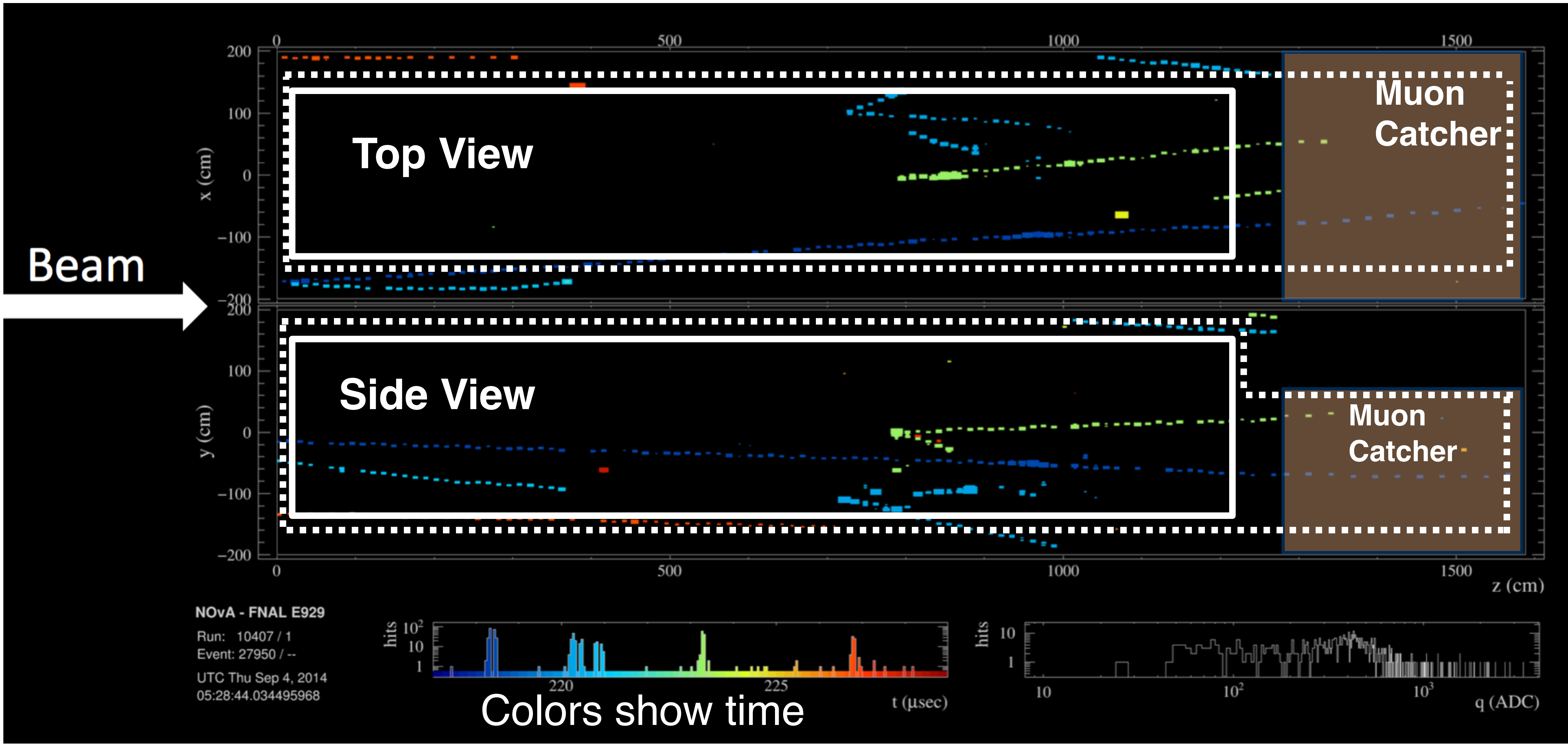
Interactions in the ND

- Hits associated in time and space are used to form a candidate interaction. Tracks and showers are reconstructed from these hits.



Events Display

- Vertices should be inside a fully active (fiducial) region to cut rock muons.



- Muon candidates should be contained in the active region + Muon Catcher and any other track only in the active region to avoid shower leaking.

Simulation Strategy

- We use **G4NuMI** for the beam simulation, **GENIE** (2.12.2) for the neutrino interactions and **GEANT4** (4.10.1) for propagating the particles.
- The **central value** prediction is made from:
  - The beam: correction of the hadrons production yield in the beamline.
  - The cross section: tuning is applied to account for nuclear effects knowledge
- **The beam and cross section systematics** are determined by hadron production uncertainties and beam components misalignments, and the GENIE reweighting scheme, respectively.
- **The simulation of the intensity dependent of rock muon rates** use data and it is integrated overlaying with the neutrino events .
- **The detector response** is also simulated and the uncertainties on the calibration parameters are dealt with systematic shifted MC.

Analyses Presented Today

- NC Coh π^0
- ν_μ-CC Semi-inclusive π^0
- ν_μ-CC Inclusive
- ν_e-CCInclusive
- ν_μ-CC Semi-inclusive π^{+-}
- $\overline{\nu}_\mu$-CC Semi-inclusive π^0
- ν_μ-CC 0 π

First results

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Analyses in their first stages

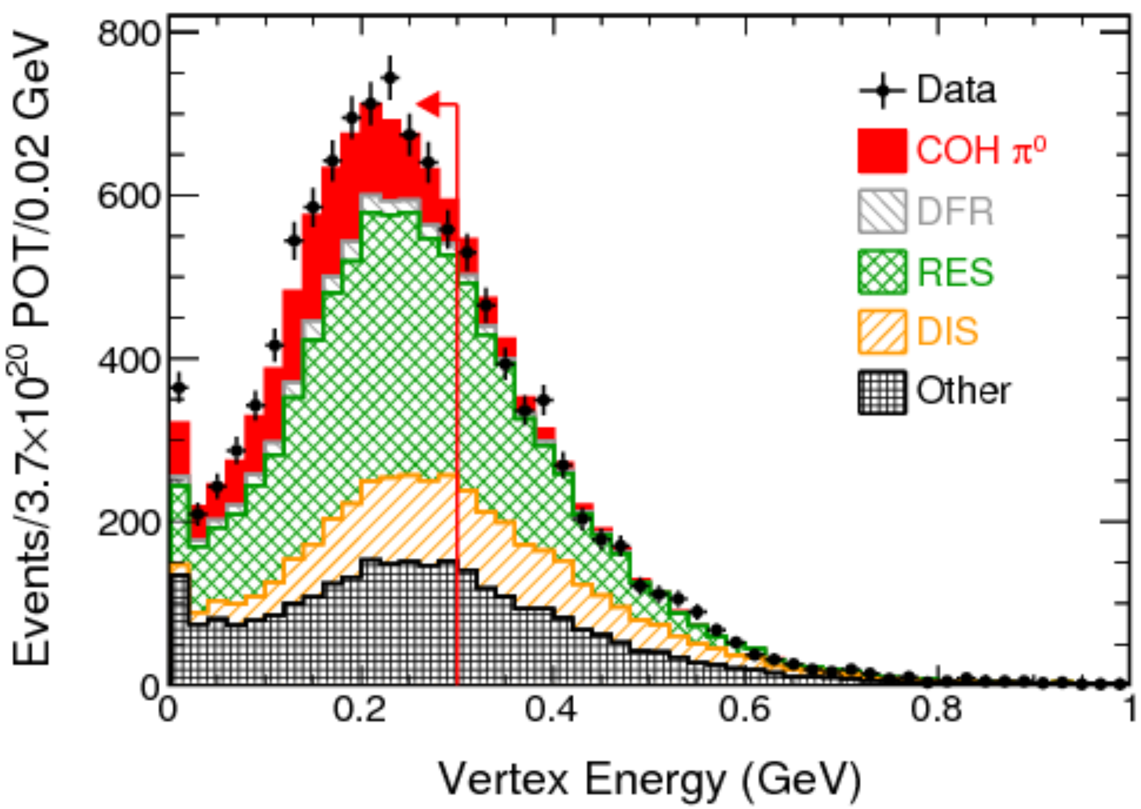
π^0 Results

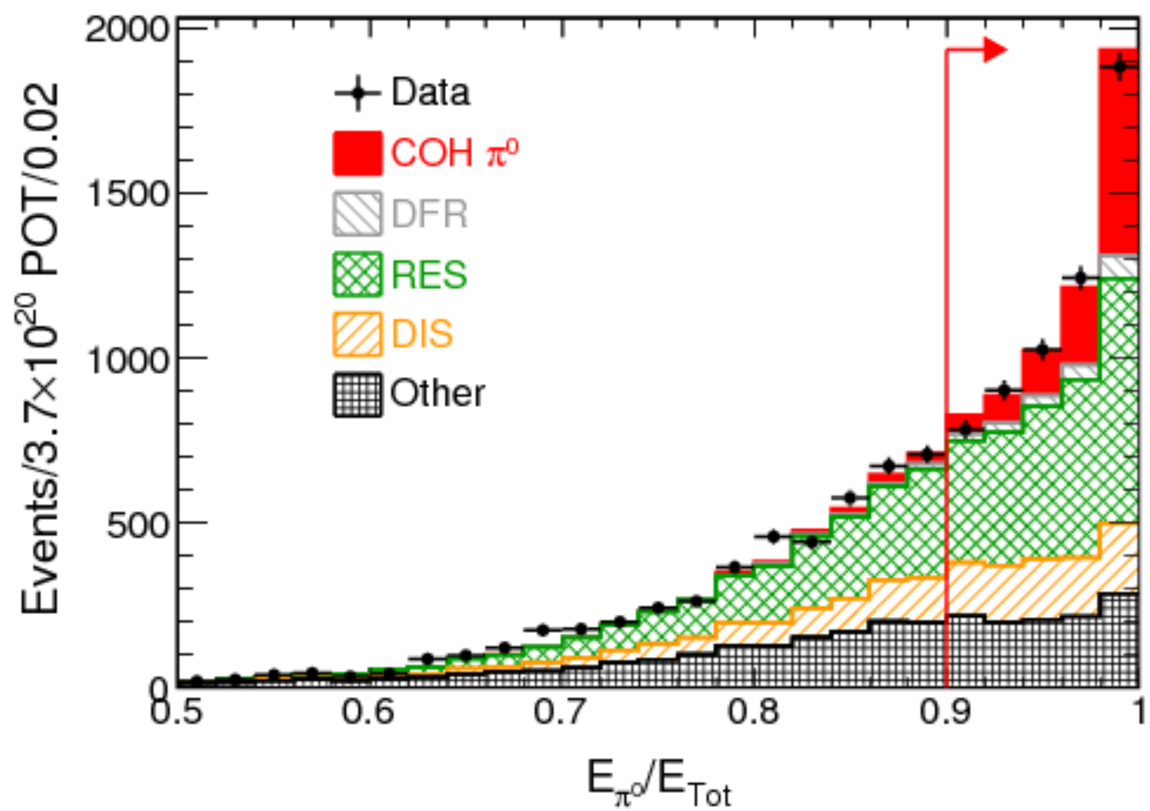
- NC Coh π^0
- ν_μ-CC π^0

Fermilab public presentation:
https://vms.fnal.gov/asset/detail?recid=1952073

NC Coherent π^0

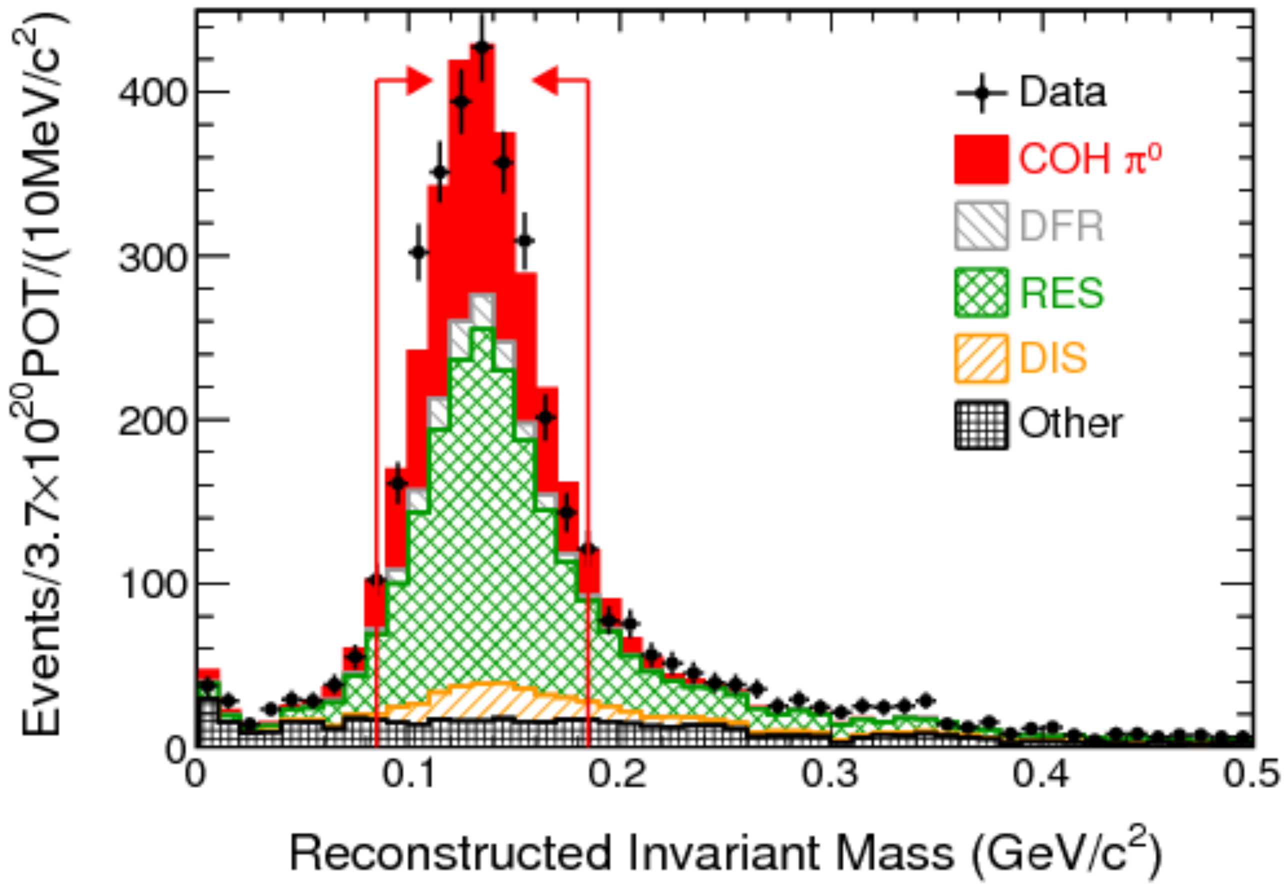
- **Measured: flux-averaged total cross section.**
- Cross section is relatively small compared to other π^0 production modes.
- Construct a NC-π^0 ID: exclude muons and identify two photons by dE/dx-based likelihood.
- Background (dominated by **NC RES** and **NC DIS**) is constraint by using signal and control samples:



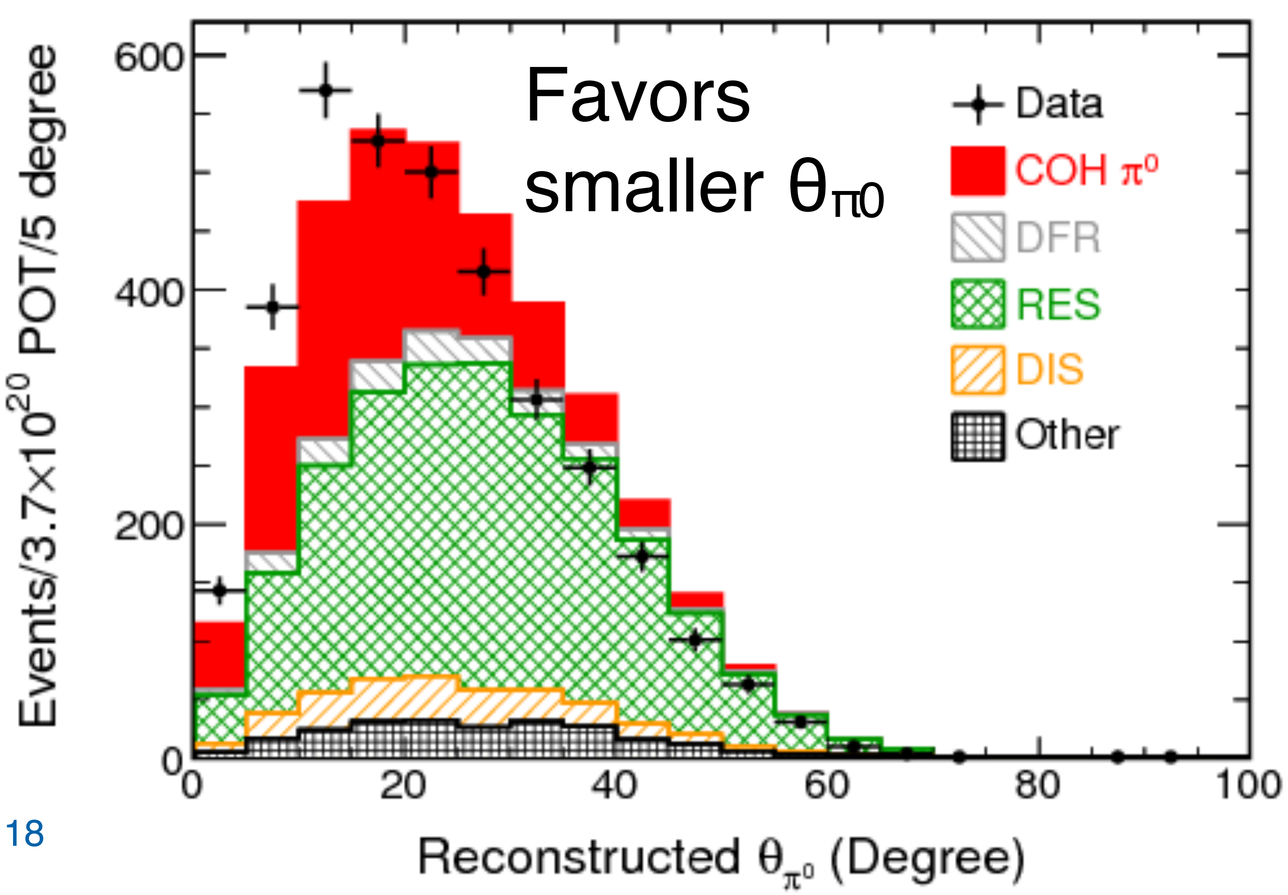


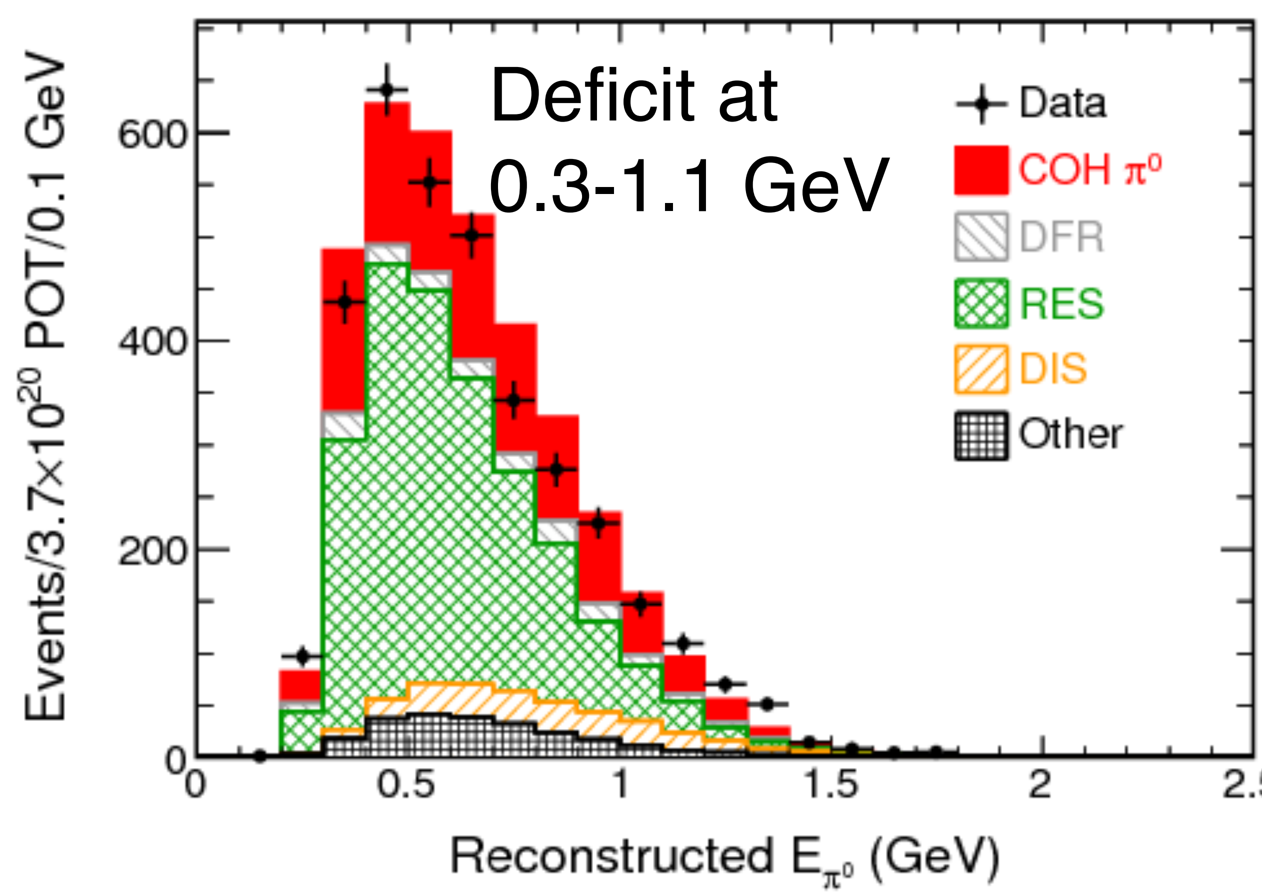
NC Coherent π^0

- Cut on invariant mass further reduces background.



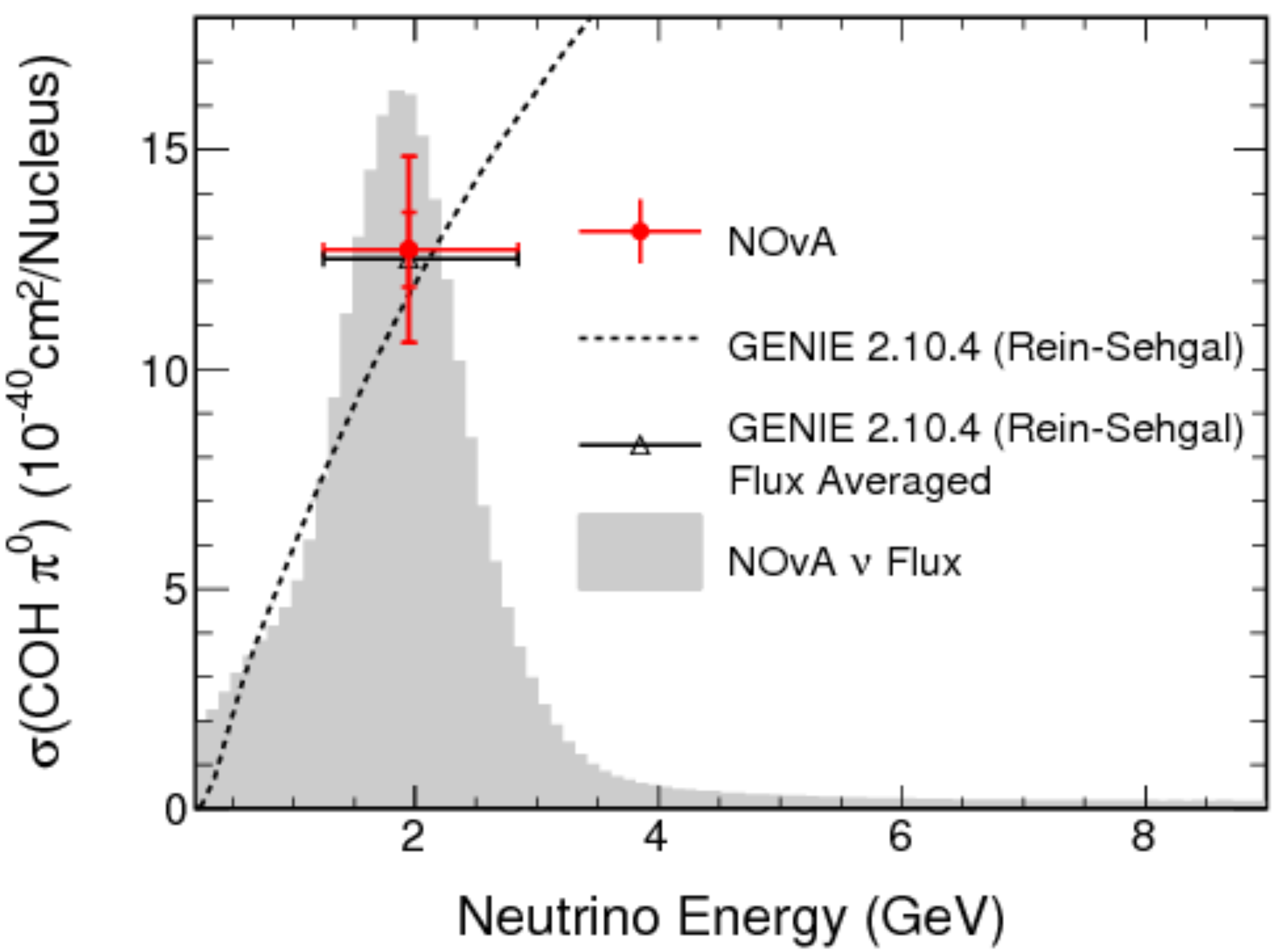
- Coherent signal results by subtracting normalized background from data in the Energy-angle π^0 space.





Results

$$\sigma = \frac{N_{Data,selected} - N_{Bkg,norm}}{\epsilon \times N_{Target} \times \phi}$$



Source	$\delta(\%)$
Calorimetric Energy Scale	3.4
Background Modeling	10.0
Control Sample Selection	2.9
EM Shower Modeling	1.1
Coherent Modeling	3.7
Rock Event	2.4
Alignment	2.0
Flux	9.4
Total Systematics	15.3
Signal Sample Statistics	5.3
Control Sample Statistics	4.1
Total Uncertainty	16.7

- Measured flux-averaged cross-section:

  σ = 14.0 ± 0.9(stat.) ± 2.1(syst.)x10^{-40} cm^2/nucleus

- Quite good agreement with GENIE's Rein-Sehgal model prediction.

Paper submitted to PRD (arXiv:1902.00558)

ν_μ Semi-inclusive π^0: $\nu_\mu + A \rightarrow \mu^- + \pi^0 + X$

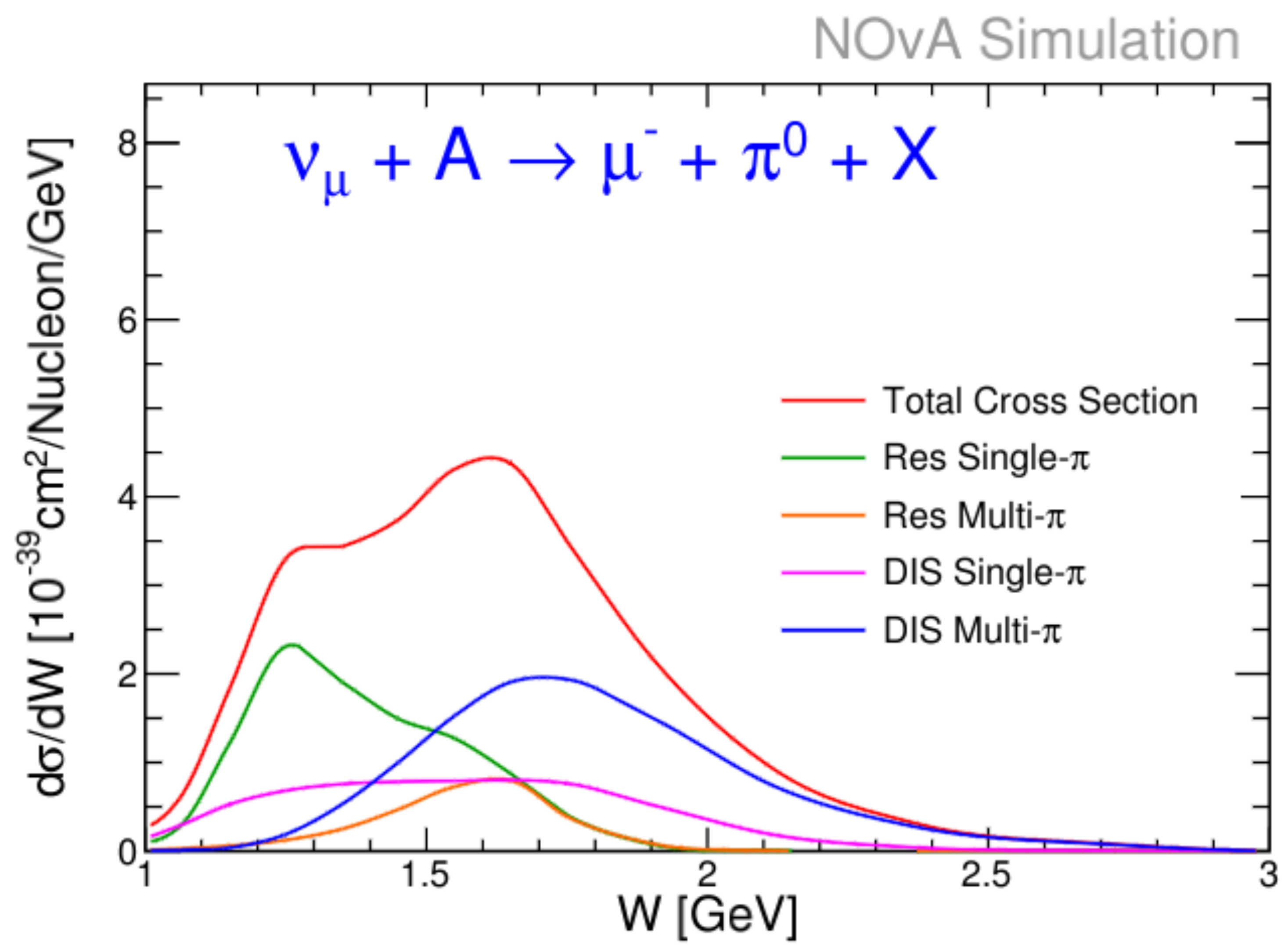
- **Measured: flux-average cross section as a function of muon and neutral pion kinematics (angle respect to the beam and momentum), Q^2 and W.**

- Signal has contributions from RES and DIS (multi-pions)

A) NC background rejected by deep learning techniques (arXiv:1906.00713 [physics.ins-det])

B) Photon identification based on photon kinematics.

C) Use a template fit of MC-predicted shapes of signal and backgrounds to the data.



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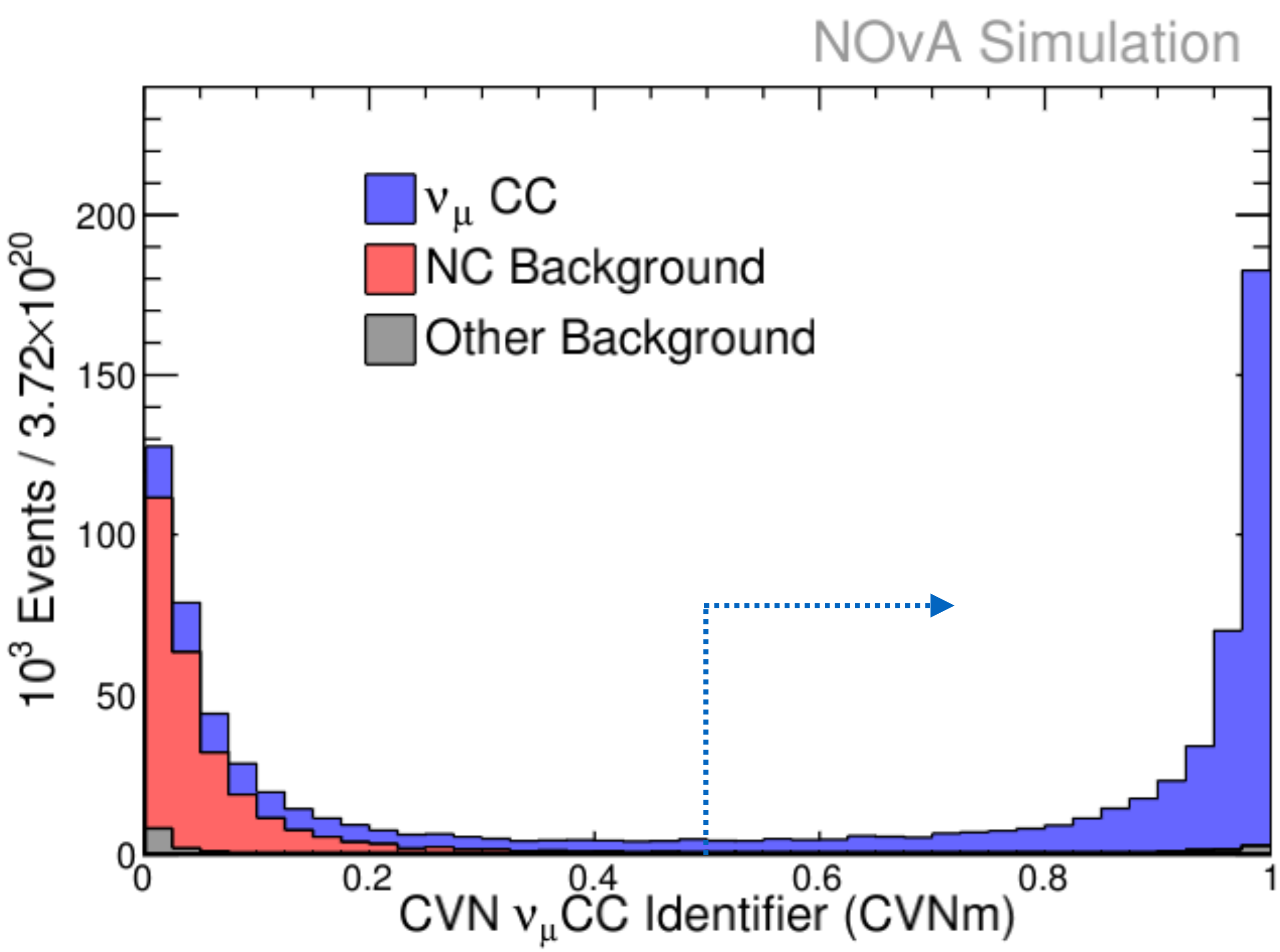
A) NC Rejection and Signal Enrichment

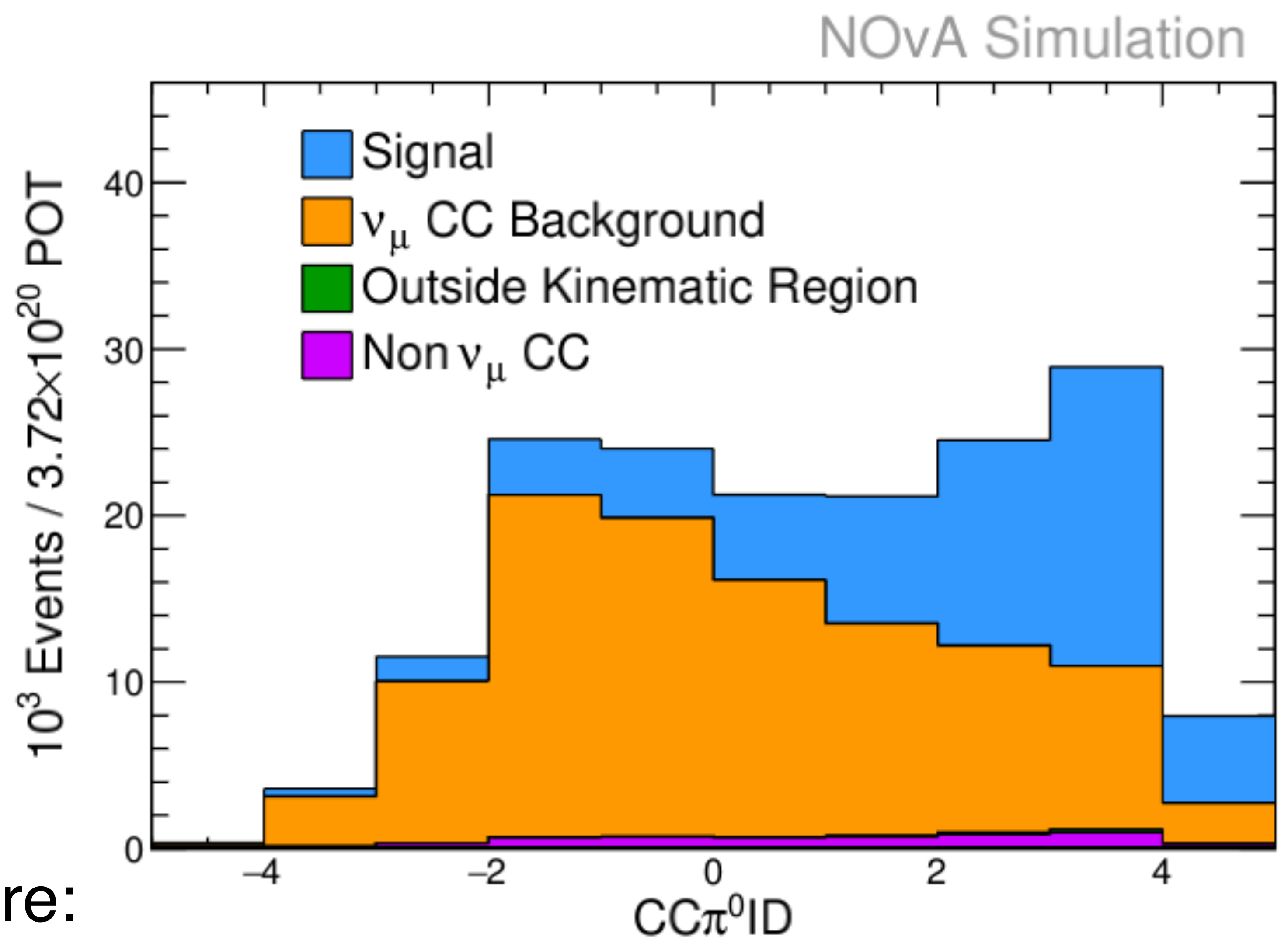
- We use Convolutional Neural Network PID (CVN) to reject NC.



- CVN trained to select ν_μ CC events.
- 1.7% of sample after CVNm cut

- We use also CVN trained to classify events by GENIE interaction mode (efficiency=23%)
    - Select only events CVN classified as RES-like or DIS-like.
    - Reject background events classified as QE-like or Coh-like.

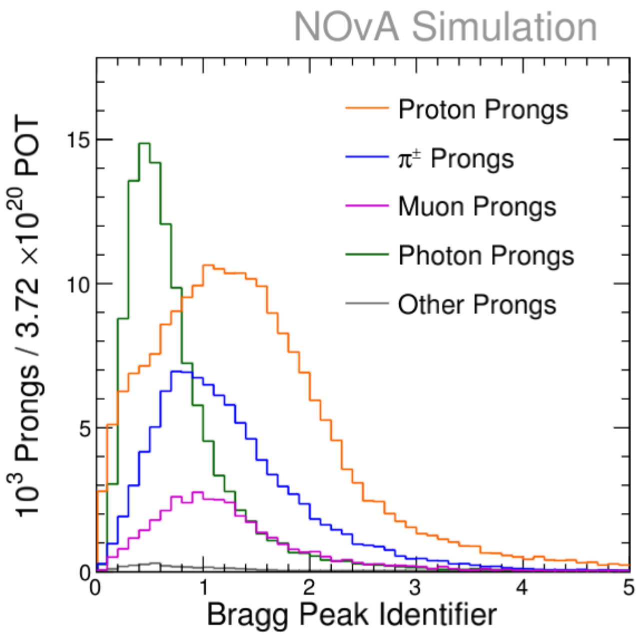
B) π^0 Identification

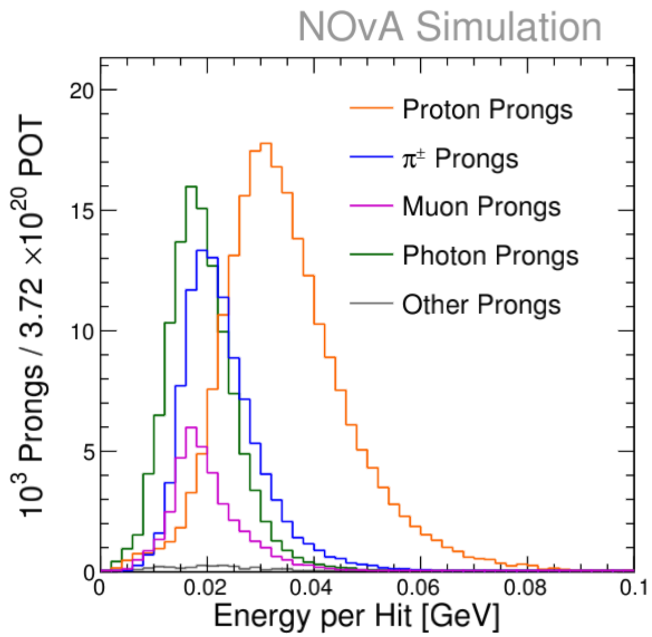


- CCπ^0ID: defined as highest photon BDT score in event.

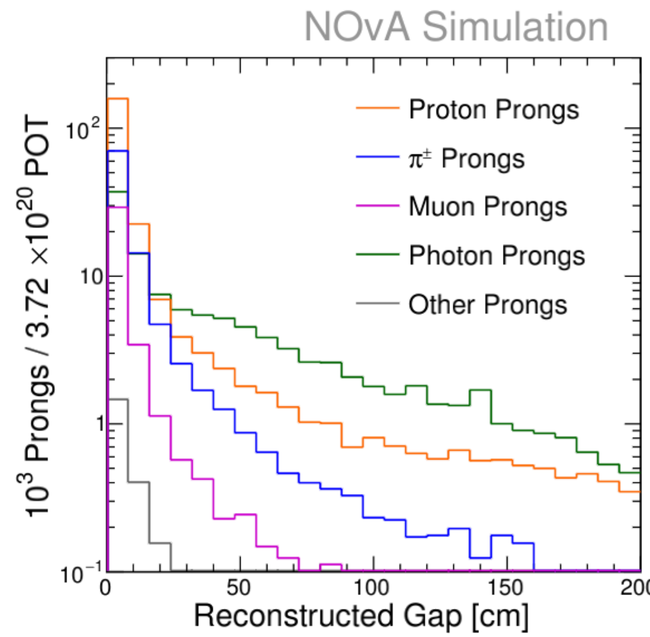
- Developed four-variable photon score:

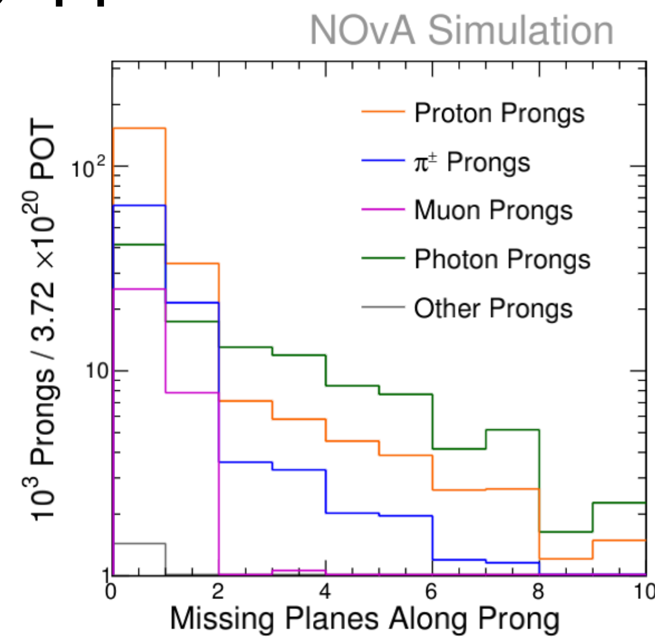
Describe dE/dx





Describe “gappiness"



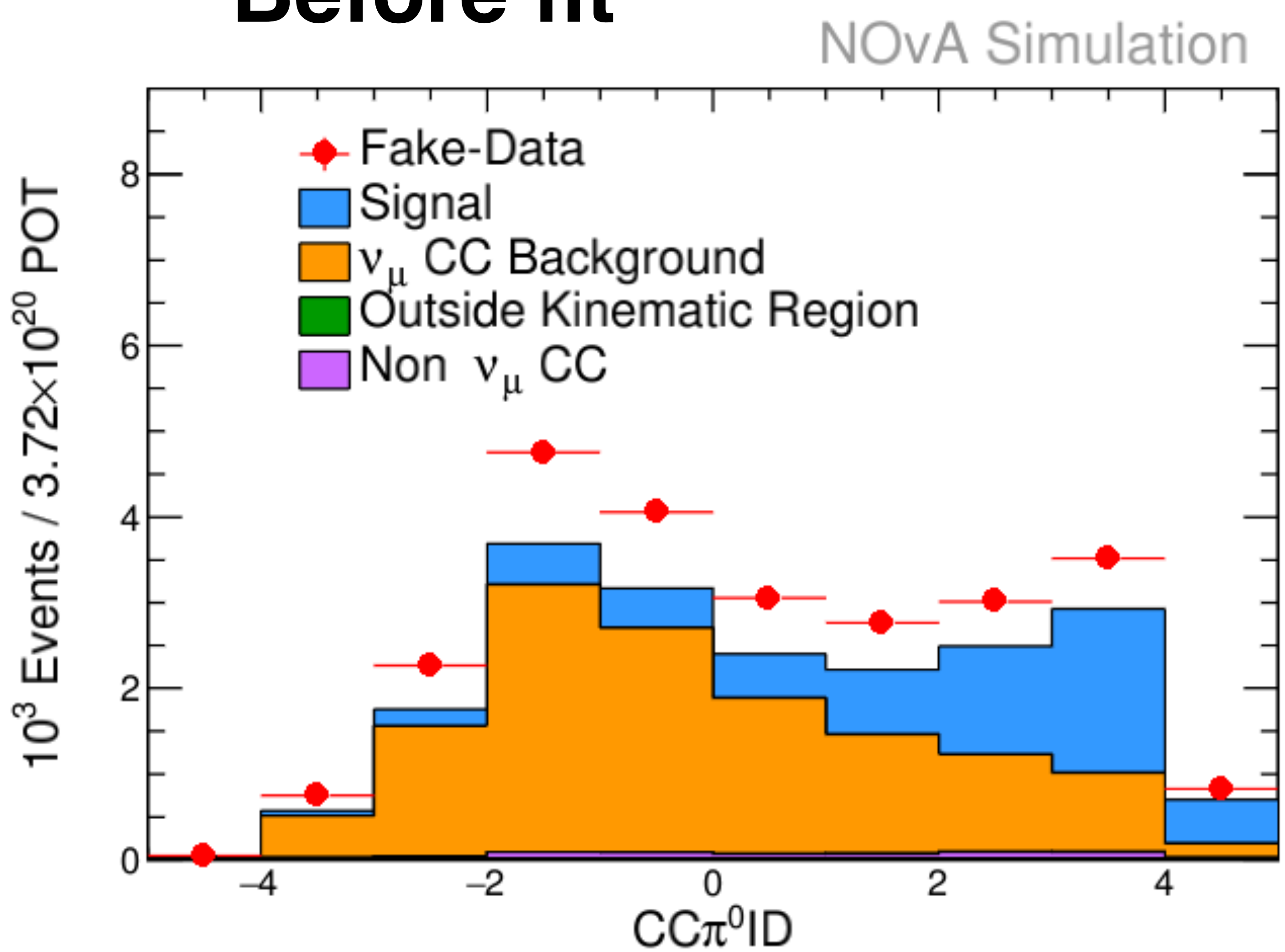


C) Constraining Simulation: Template Fitting

Example: $0.5 < p_\mu < 0.6$ GeV/c

- Apply a data-driven constraint to simulation: a template fit
- Procedure assumes the simulated $CC\pi^0$ID shape but allows signal and background normalization to float

Before fit



Measurement is differential: must perform template fit in every kinematic bin separately

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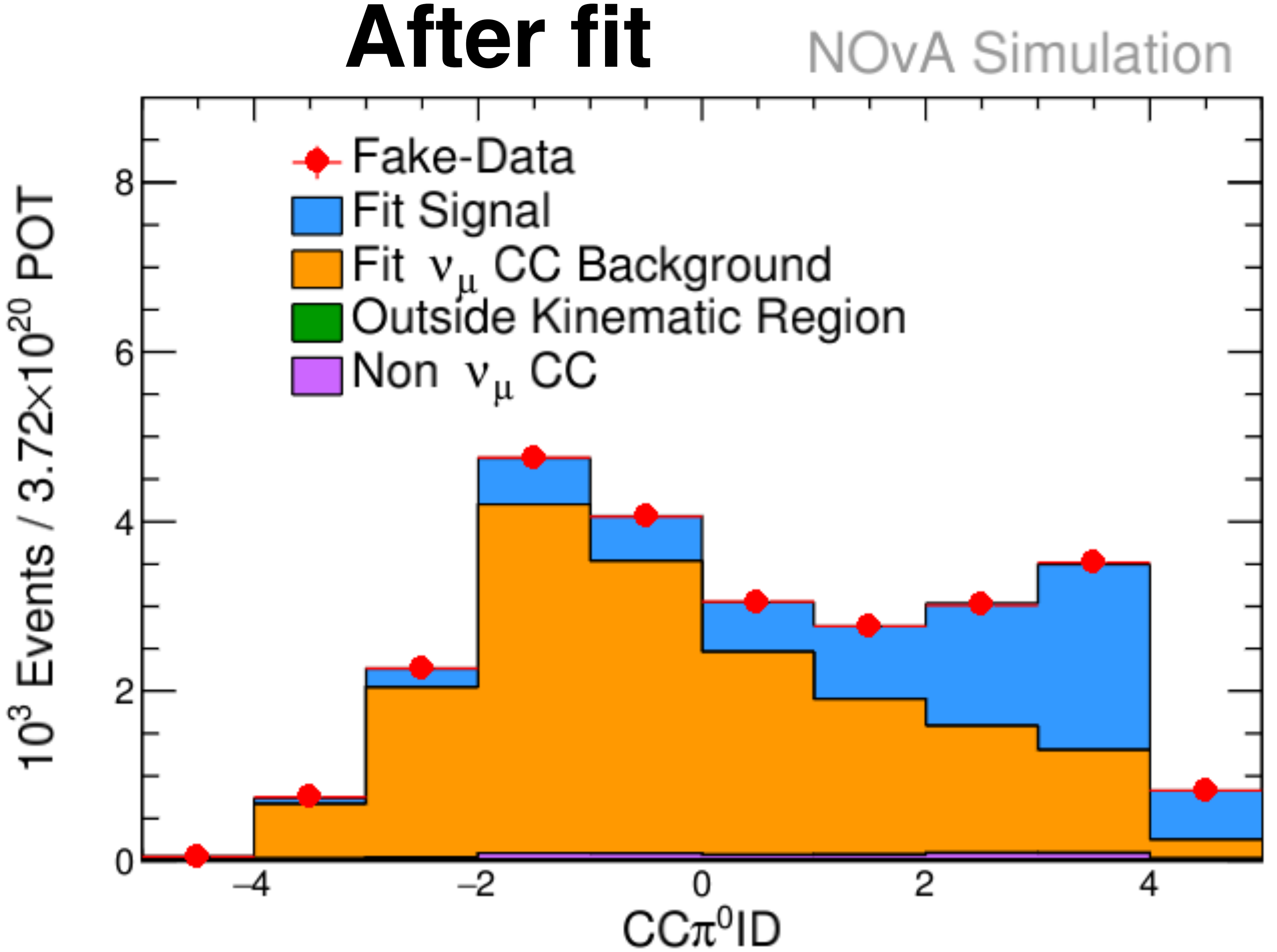
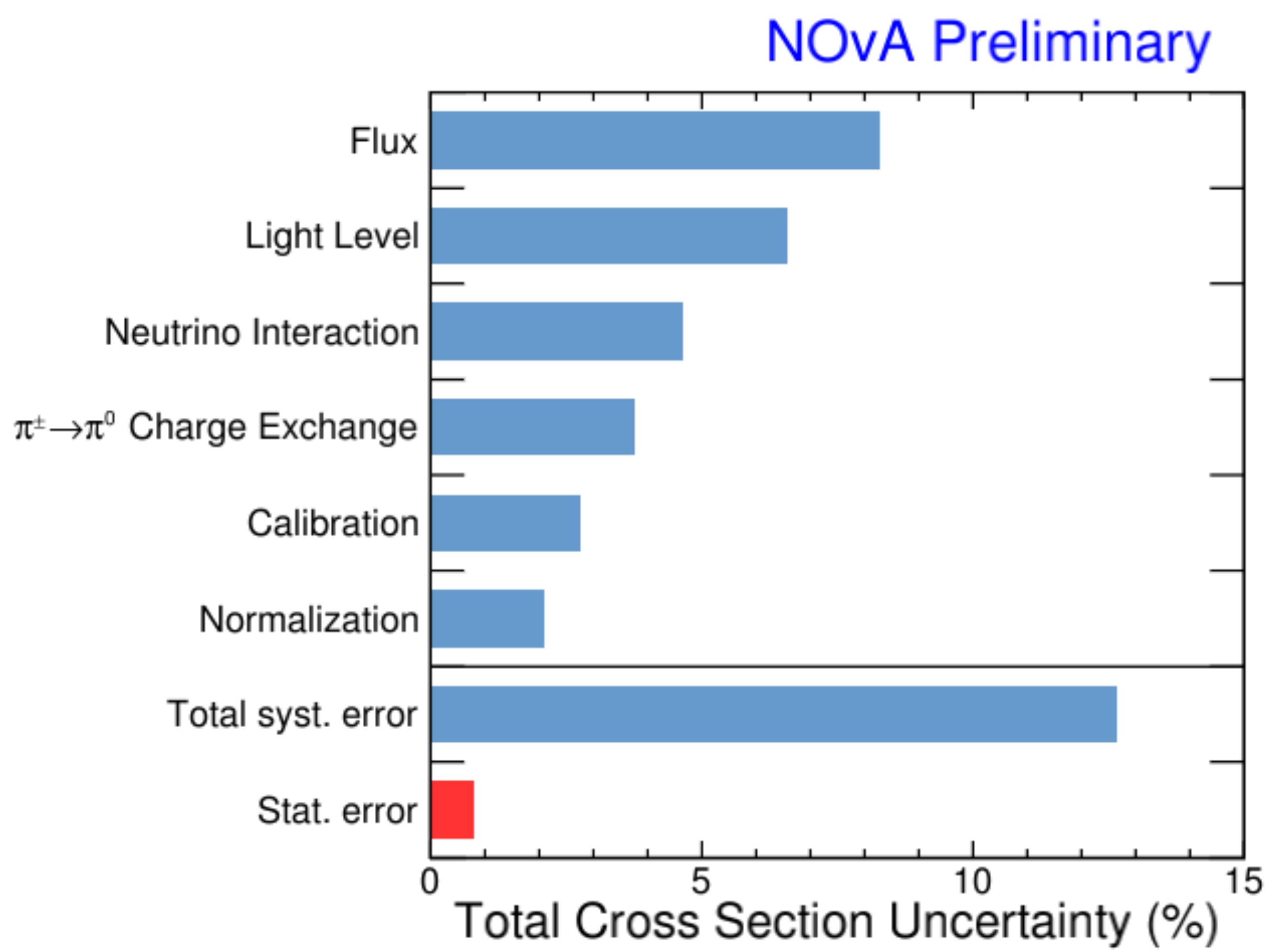
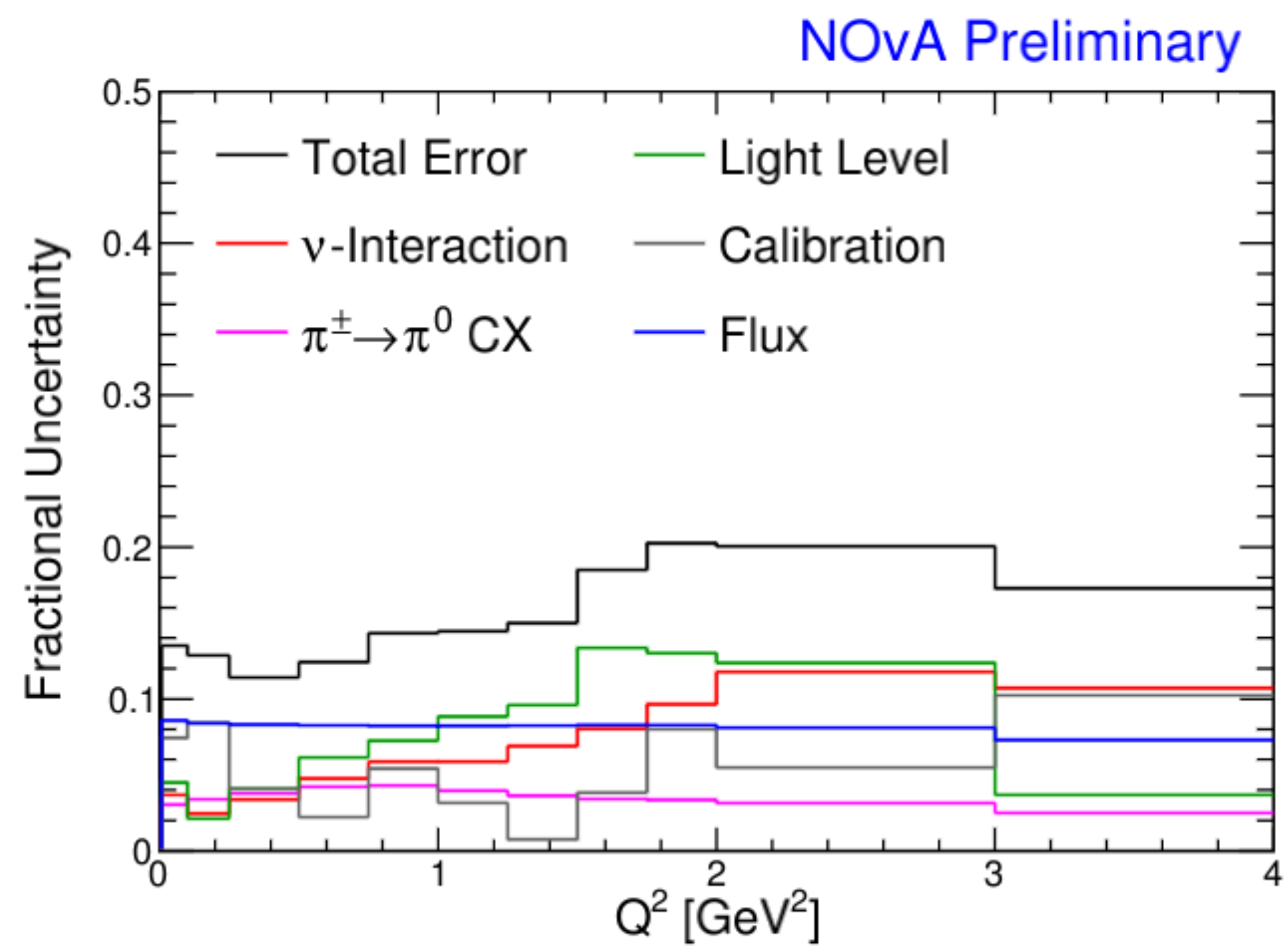


Measurement is differential: must perform template fit in every kinematic bin separately

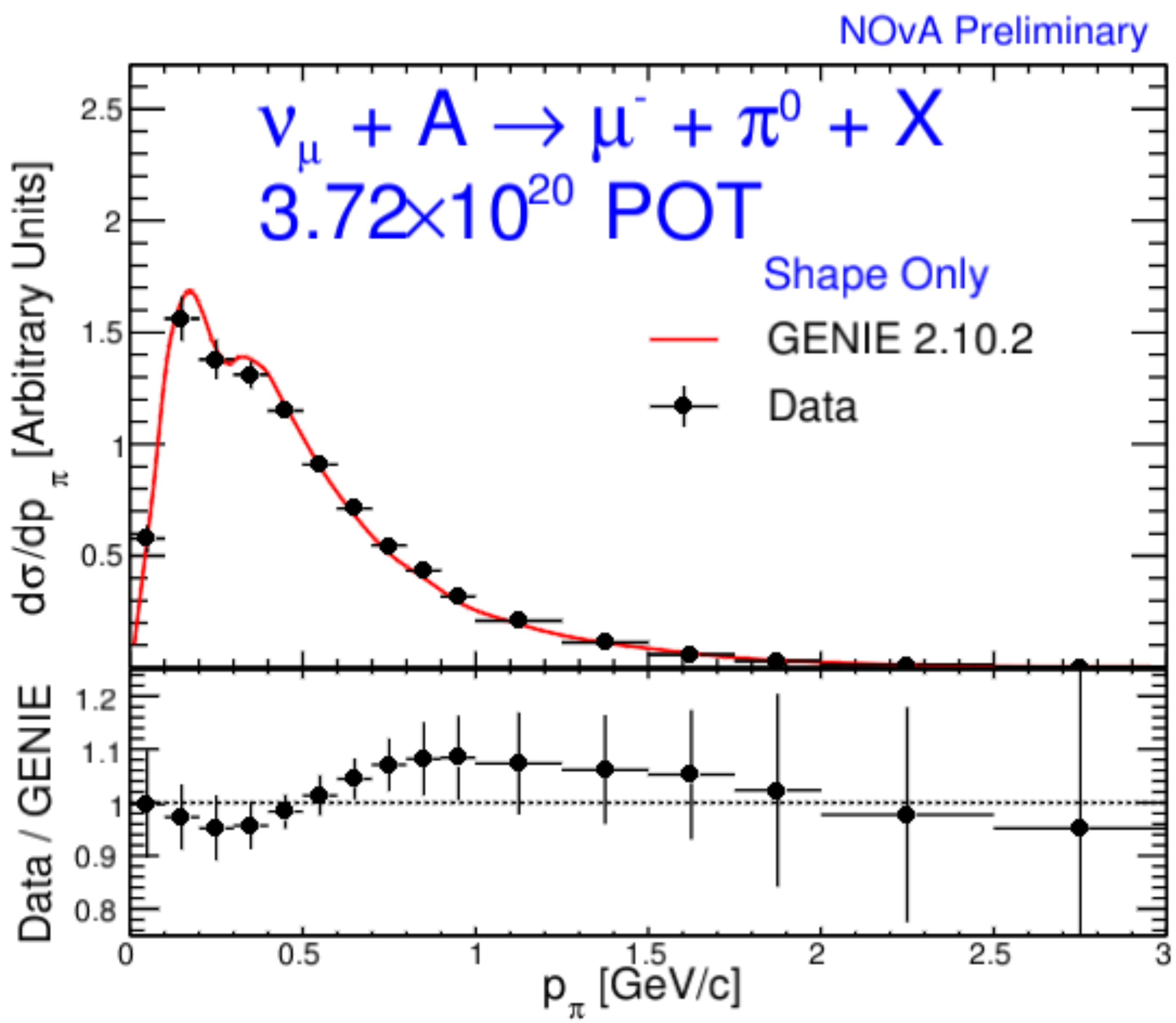
Uncertainties

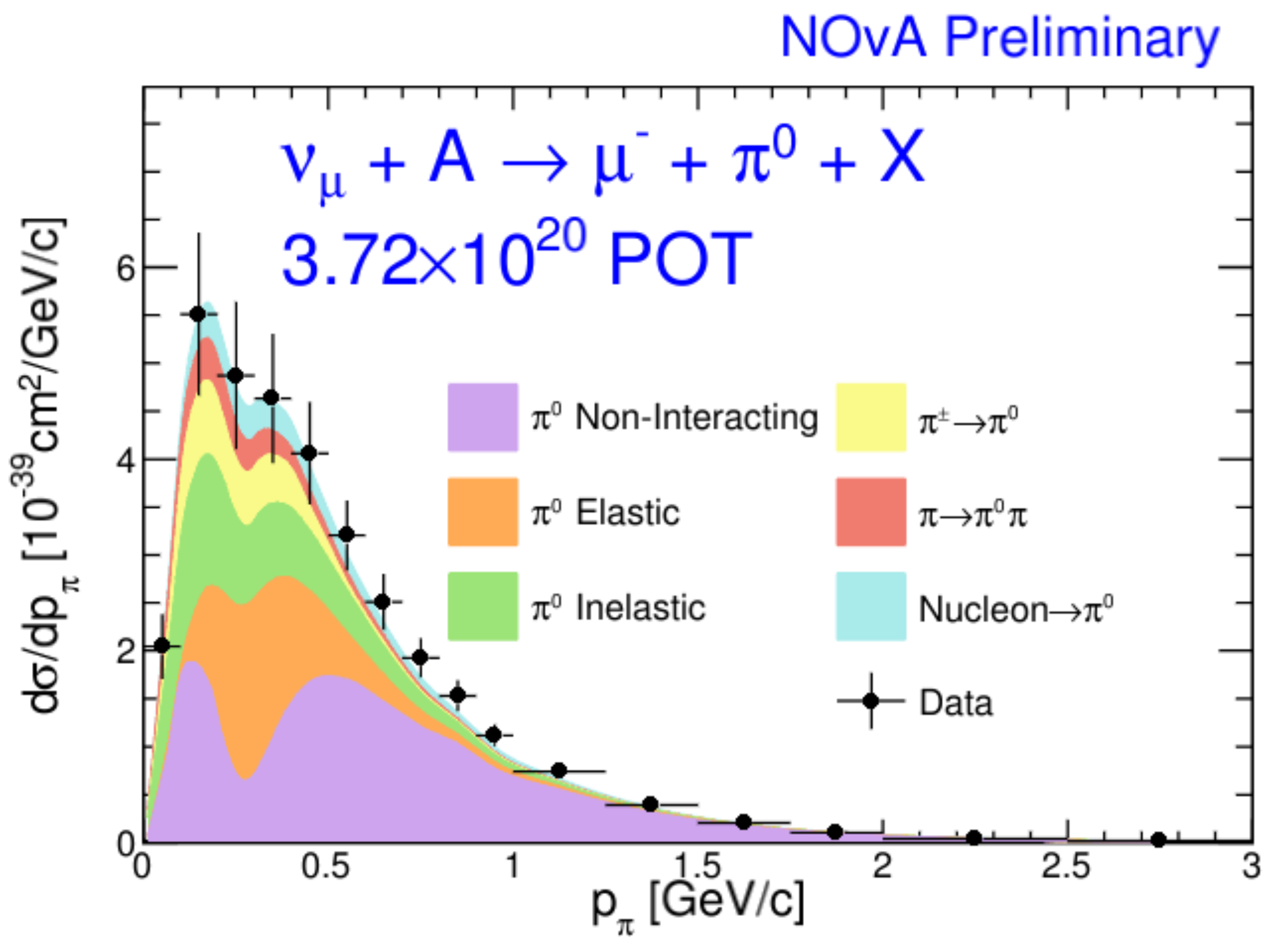
- Systematic dominated measurement dominated by the flux, light level and cross section model.





$d\sigma/dP_\pi$ Cross Section





- **We expect to deliver the flux-average cross section of muon and neutral pion kinematics (angle respect to the beam and momentum), Q^2 and W.**
  - Also, the corresponding covariance matrix
  - Detailed model comparisons.

Paper is in final Collaboration Review, publication very soon!

Inclusive Analyses

- ν_μ-CC
- ν_e-CC

ν_μ-CC Inclusive

- **Goal: double differential cross section as a function of muon kinematics ($\cos\theta_\mu$ vs T_μ).**

- **Philosophy**: this measurement is systematics-limited, so relevant **GENIE** and **detector response** uncertainties are included in the FOM:

$$\sigma = \frac{N_{sel} - N_{bkg}}{\phi T \epsilon} = \frac{P N_{sel}}{\phi T \epsilon} \Rightarrow \boxed{\frac{\delta\sigma}{\sigma} \approx \sqrt{\left(\frac{\delta P}{P}\right)^2 + \left(\frac{\delta\epsilon}{\epsilon}\right)^2}}$$

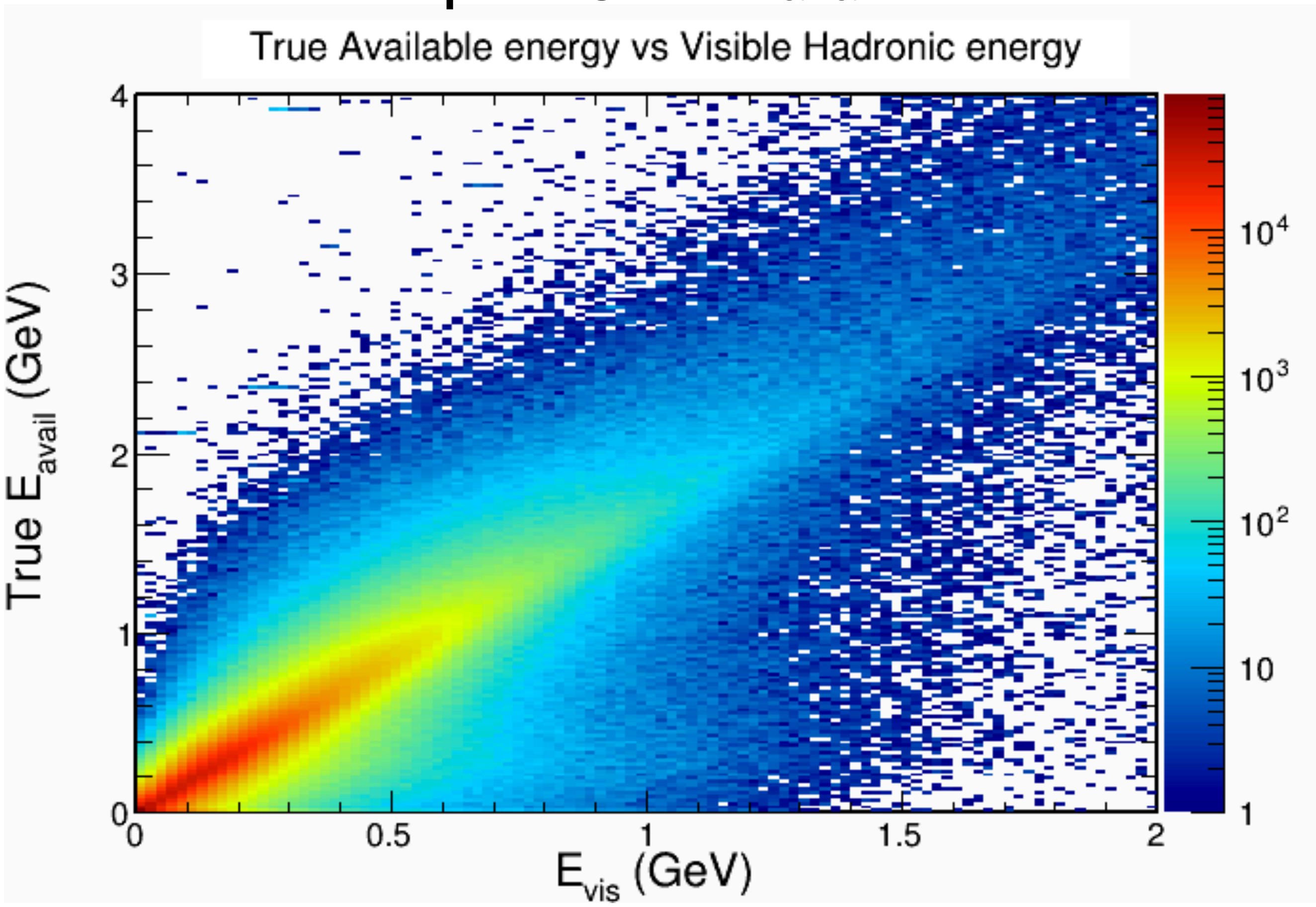
P: purity
ϵ: efficiency
ϕ: neutrino flux
T: number of targets

- Analysis is performed completely in 3D of quasi-orthogonal variables: ($\cos\theta_\mu$, T_μ, E_{avail}) and projected to 2D.

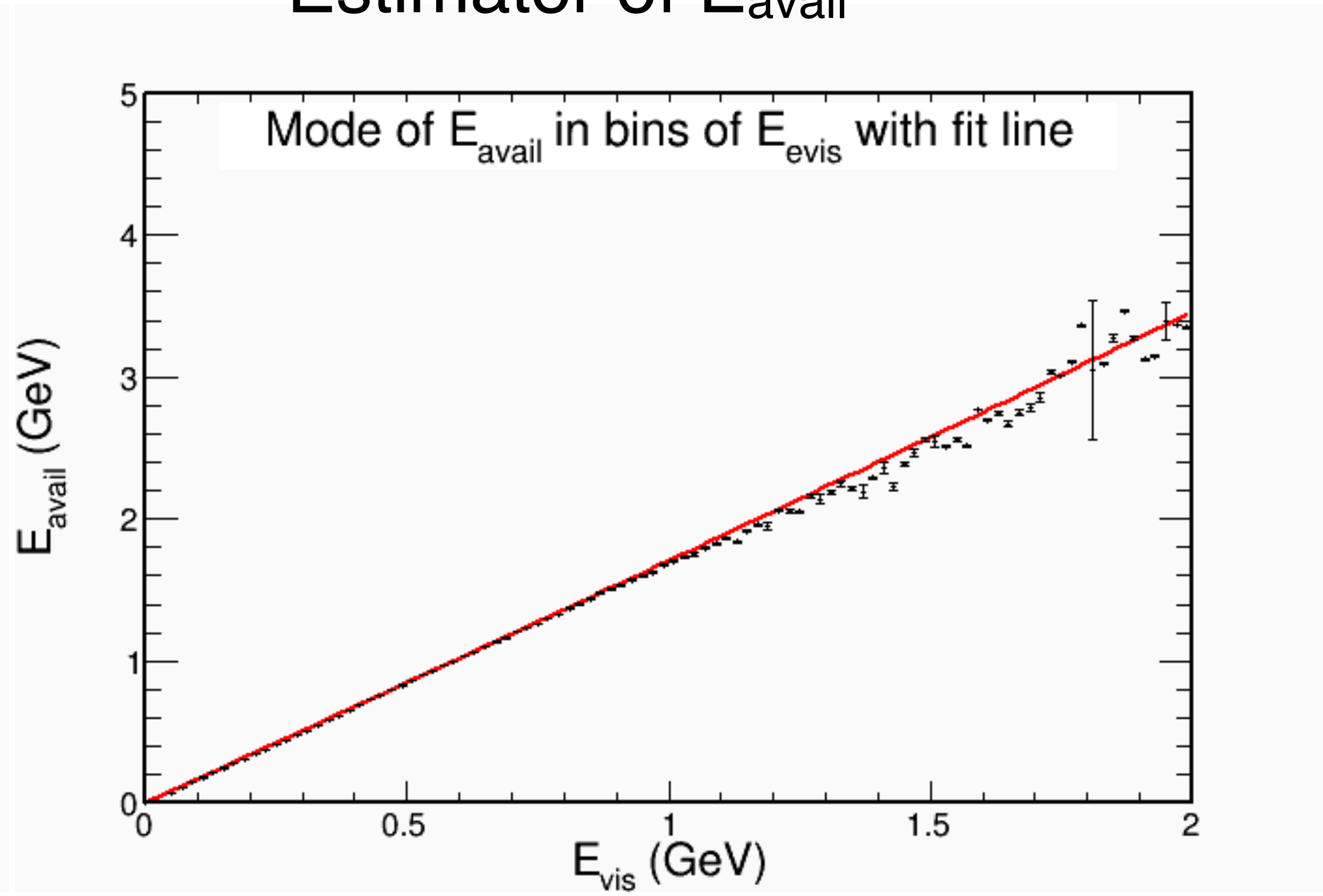
Available Energy

- E_{avail} is a proxy for the hadronic energy and independent of the muon kinematics.
  - E_{avail} is the energy that can be reliably observed in the detector with less model dependence.

Map E_{vis} vs E_{avail}



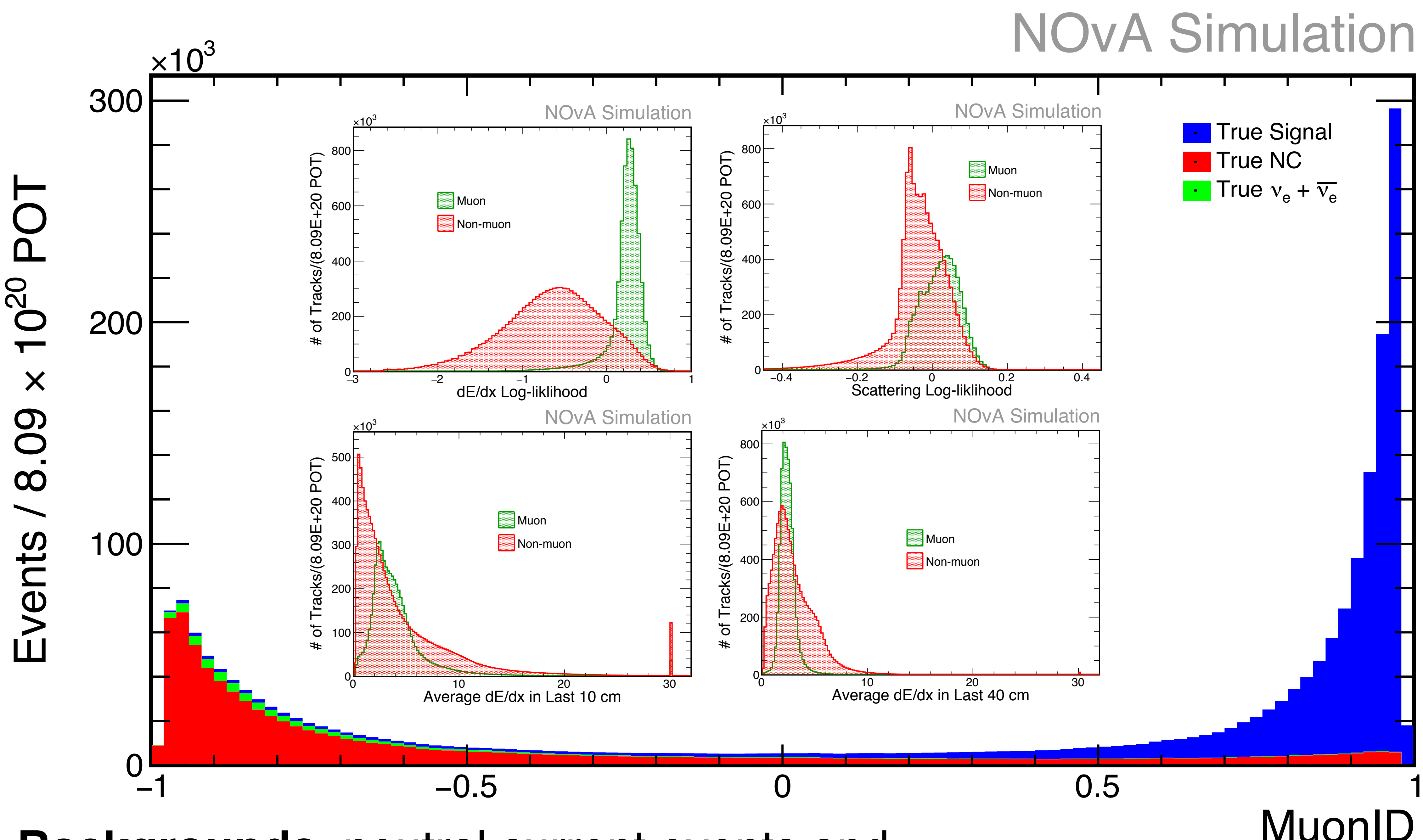
Estimator of E_{avail}



$E_{avail} \sim T_p + T_{\pi^{+/-}} + E(e, \gamma, \pi^0, K)$.

Muon ID

- A muonID using a BDT has been developed based on the dE/dx and scattering of the tracks:



- **Backgrounds**: neutral current events and ν_e.

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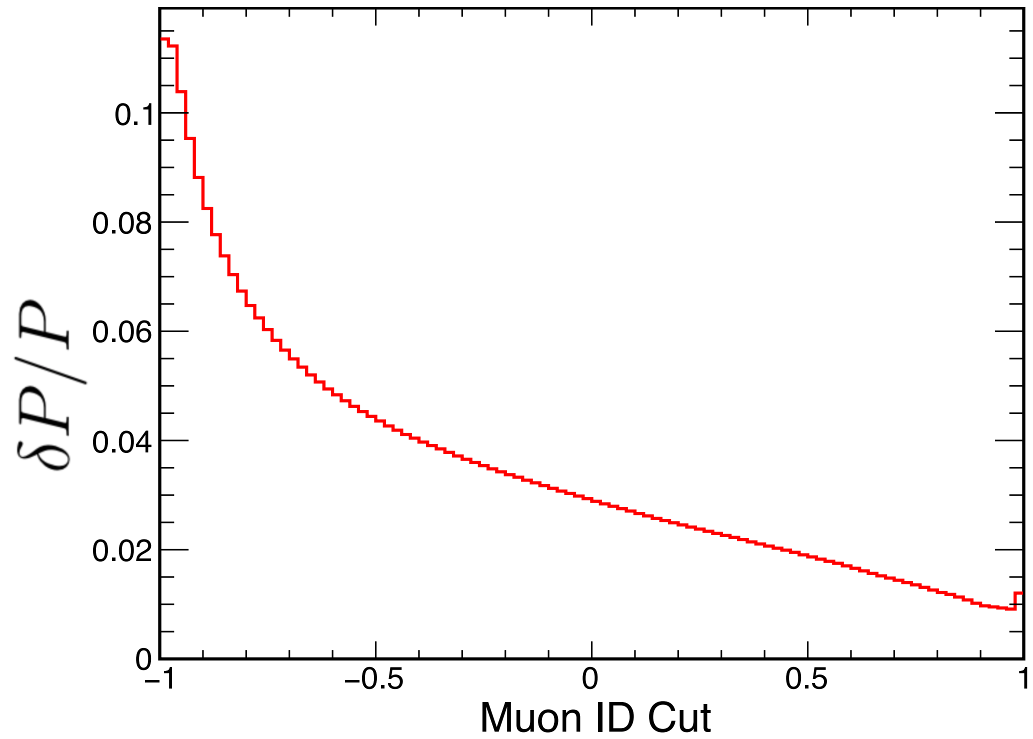
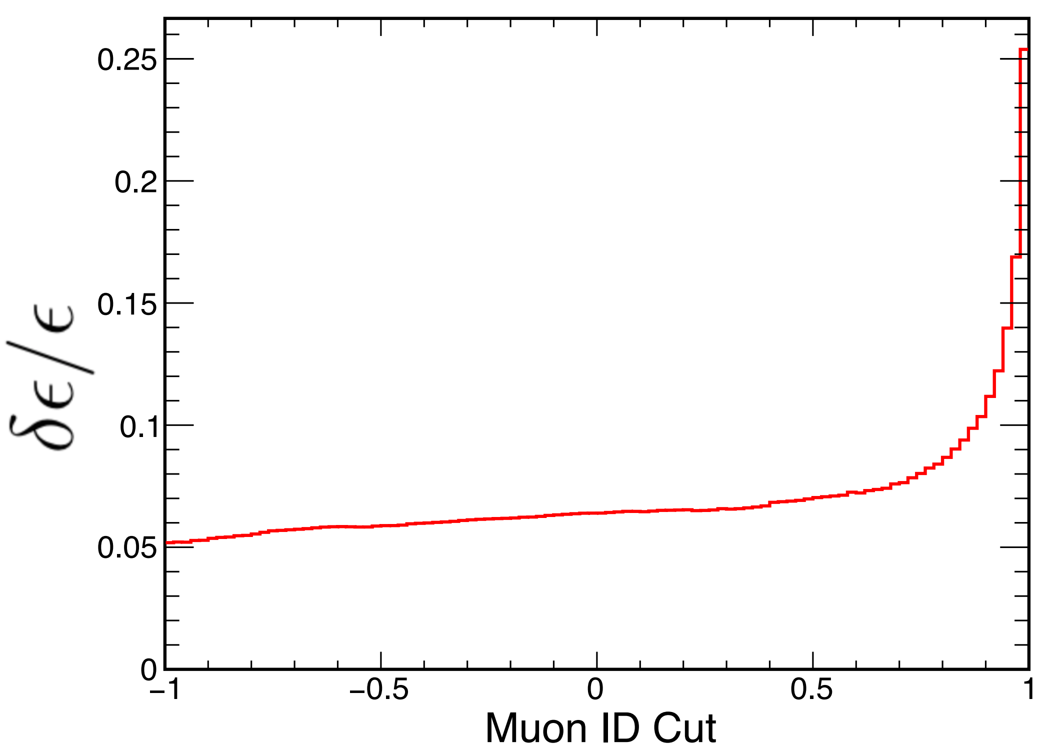
Event Selection Optimization

$$\frac{\delta\sigma}{\sigma} \approx \sqrt{\left(\frac{\delta P}{P}\right)^2 + \left(\frac{\delta\epsilon}{\epsilon}\right)^2}$$

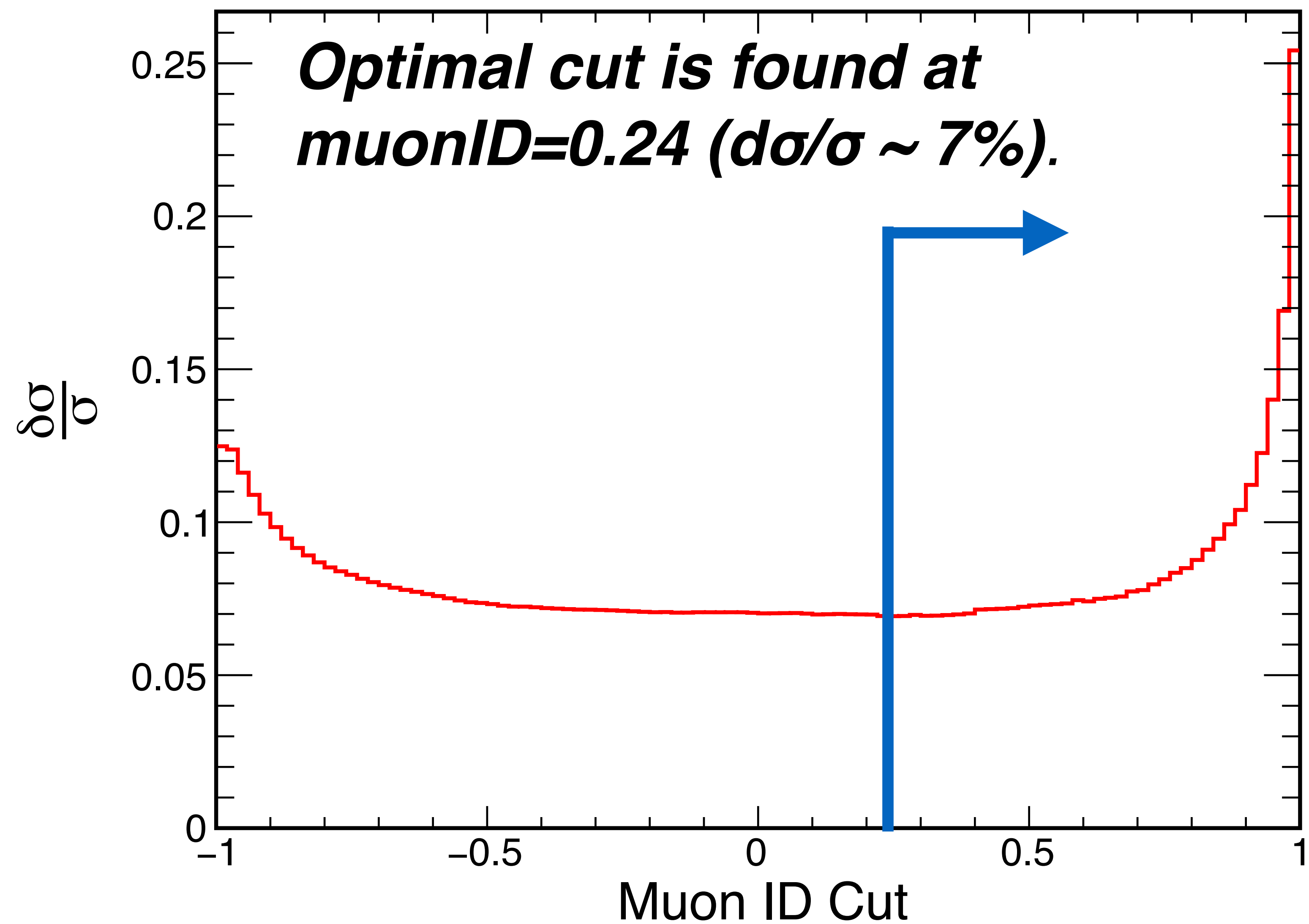
Relative Syst. Uncertainty on Purity



Relative Syst. Uncertainty on Eff.



Relative Uncertainty on Cross-section



Event Selection

- The event selection cuts include: quality, fiducial, containment and the MuonID cut.

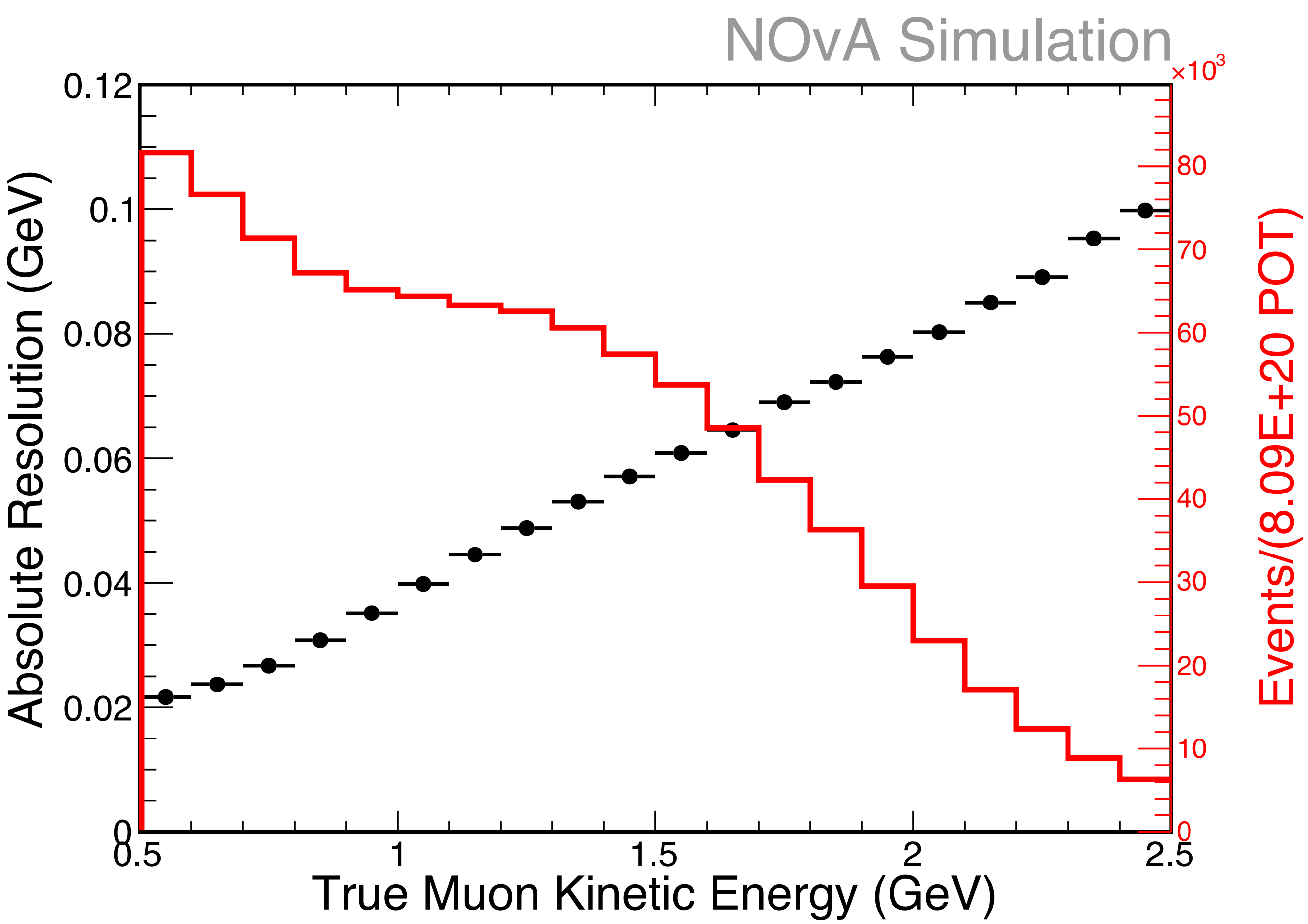
Signal CC Inc. ν_μ	CC Inc. $\bar{\nu}_\mu$	NC	CC Inc. $\nu_e + \bar{\nu}_e$	Non-fiducial
86.4 % (1.18×10^6)	2.57%	7.60%	0.44%	2.96%

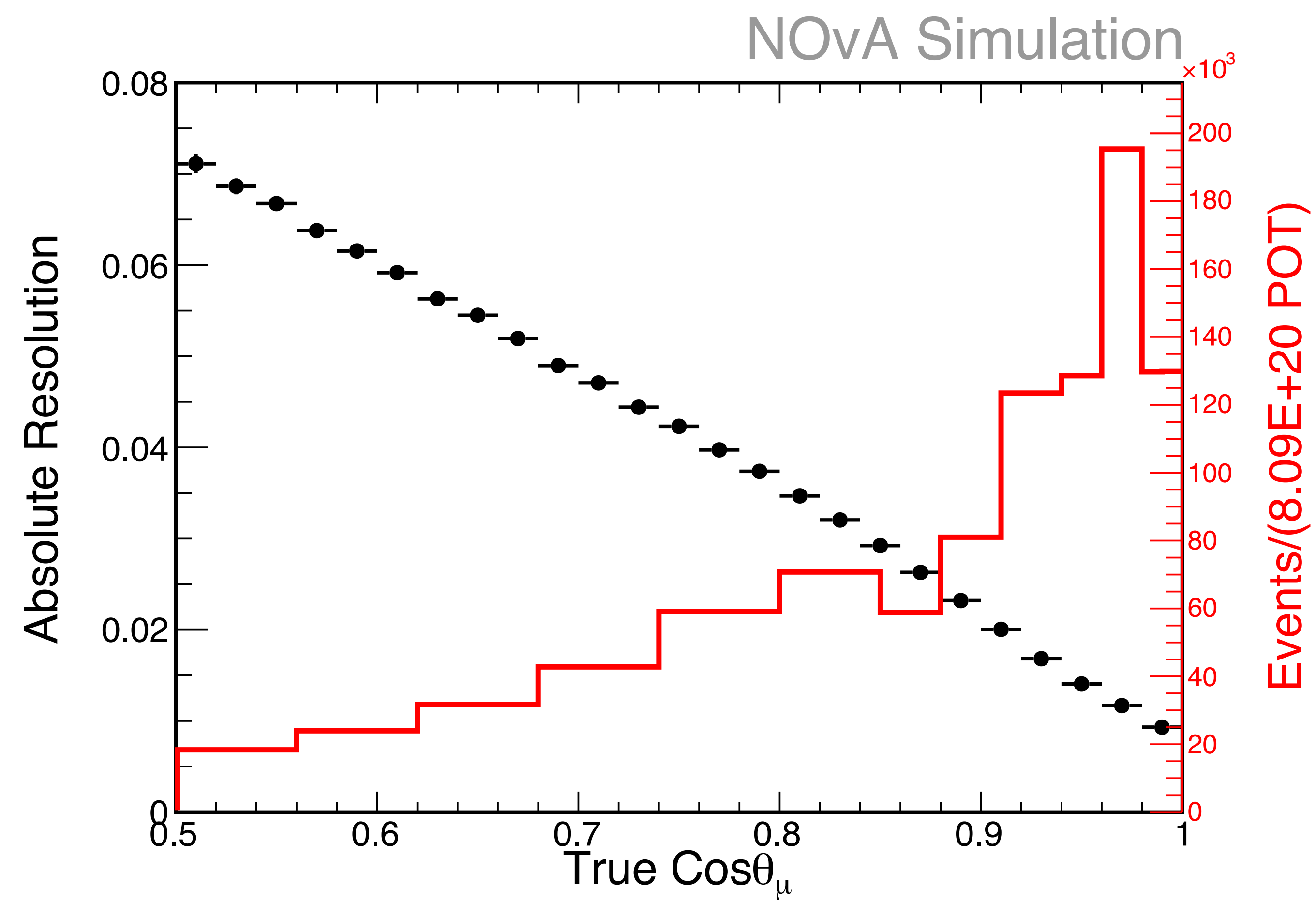
- Fraction of signal events per interaction mode:

QE	Res	DIS	Coh	MEC
20.85%	38.68%	19.80%	1.79%	18.88%

Resolution and Binning

- Muon energy resolution is ~4%. Resolution is 1-3% for shallow angles ($\theta > 45^0$).
- Binning is determined by combination of resolution and statistics.

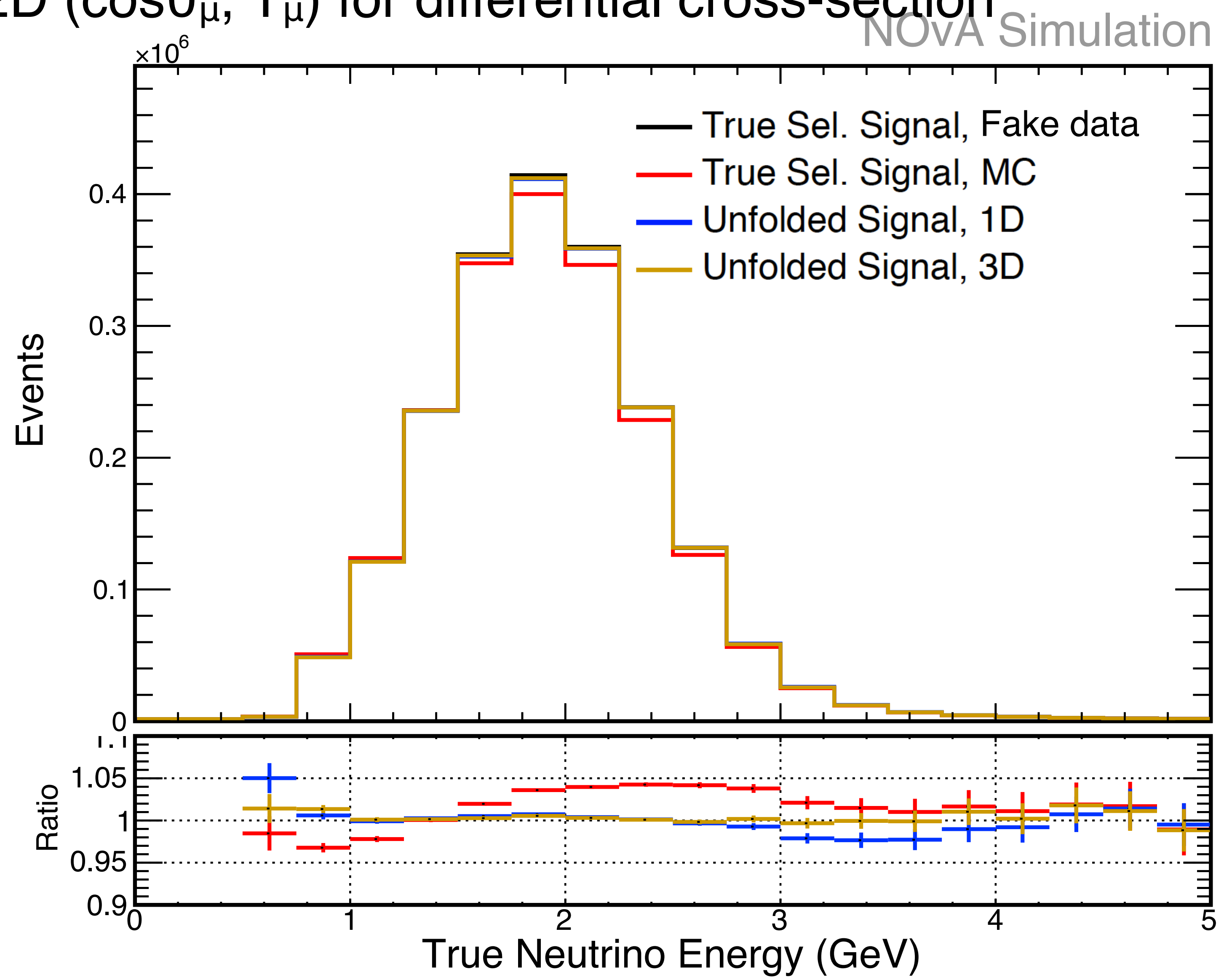




Analysis in 3D

- **Unfolding and efficiency correction are performed in 3D ($\cos\theta_{\mu}$, T_{μ}, E_{avail}).**
  - This is to take into account correlations between lepton and hadron kinematic variables.
- Projection to 1D (E_{avail}) and 2D ($\cos\theta_{\mu}$, T_{μ}) for differential cross-section measurement.

Test of the 3D vs 1D unfolding on the neutrino energy distribution:



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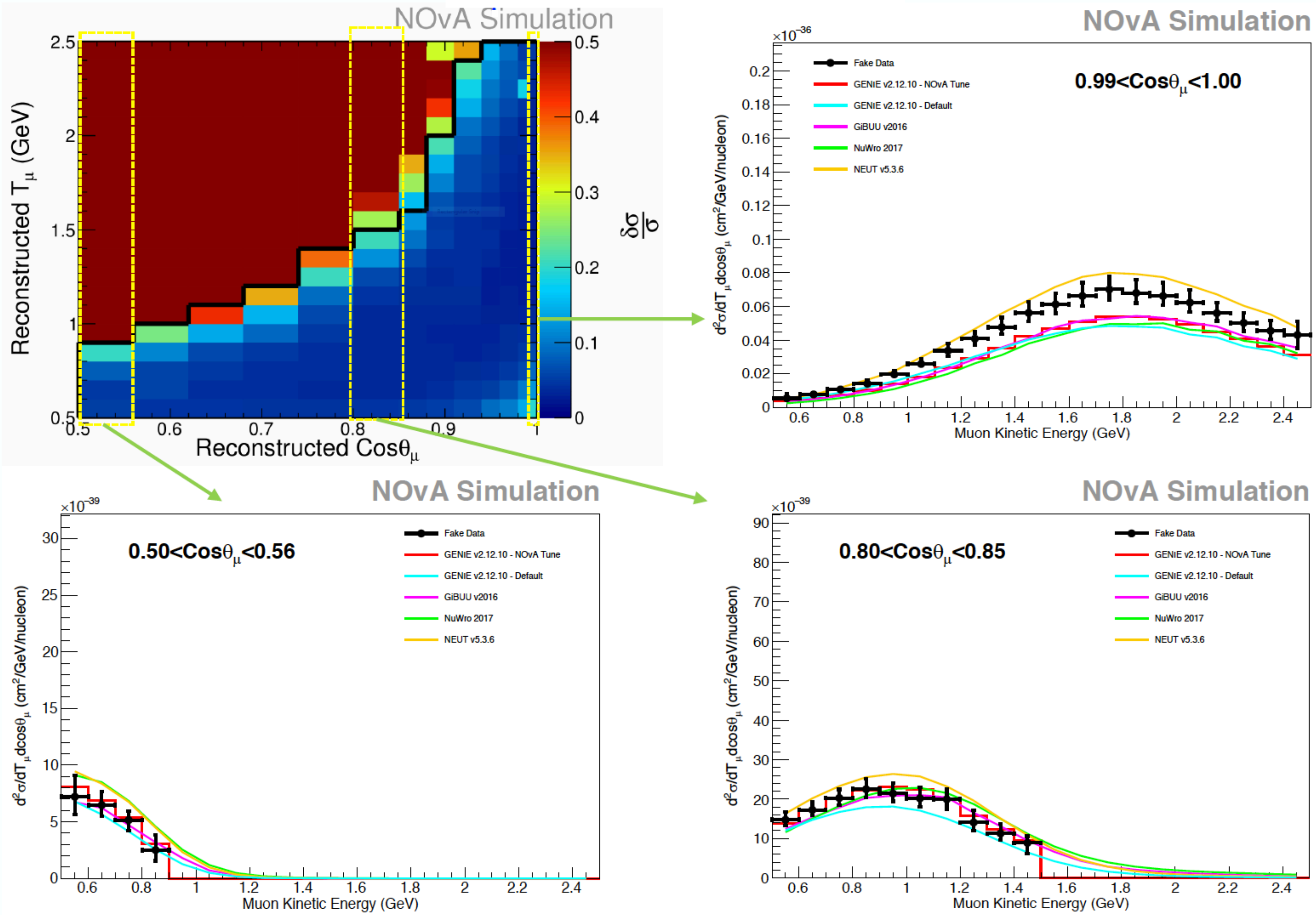
Expected Uncertainty and Mock-data Study



Analysis is in final stage… expect a publication soon!

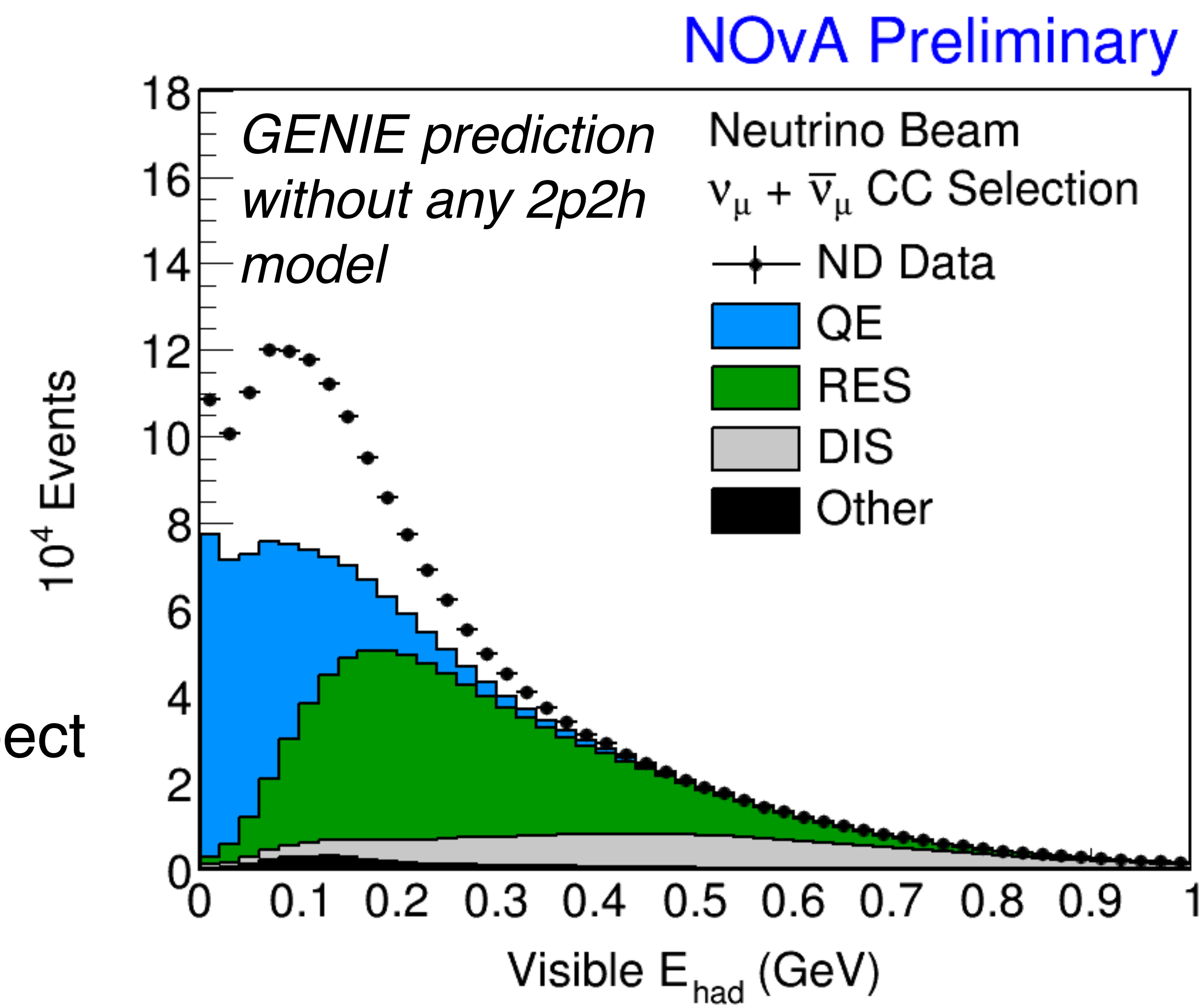
Measuring 2p2h

- **Goal: double differential cross section as a function of E_{avail} vs $|\vec{q}|$.**

Motivation:

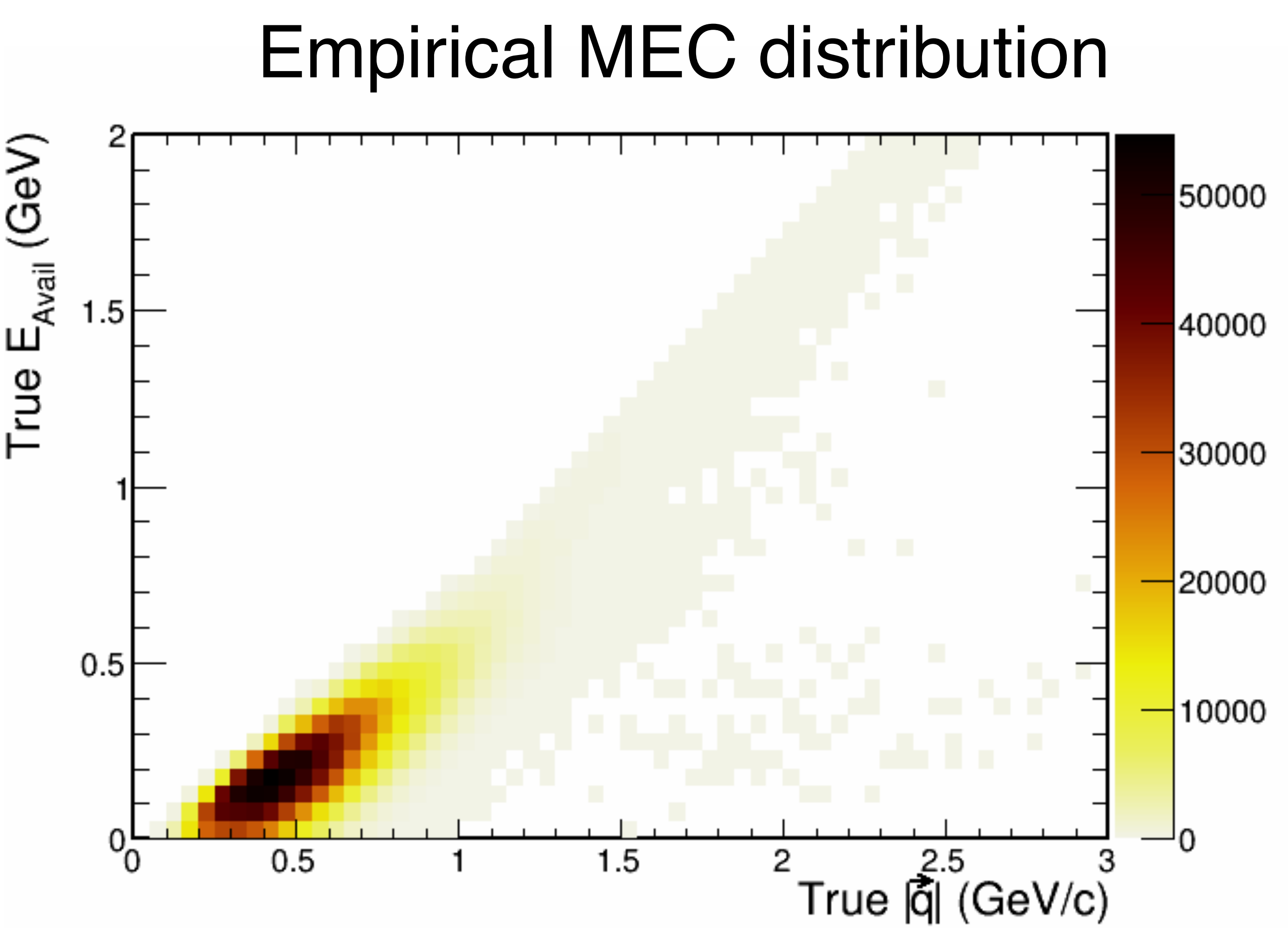
- There is at least one process that is not modeled to account of nucleon correlations inside the nucleus: **2 particle - 2 holes**

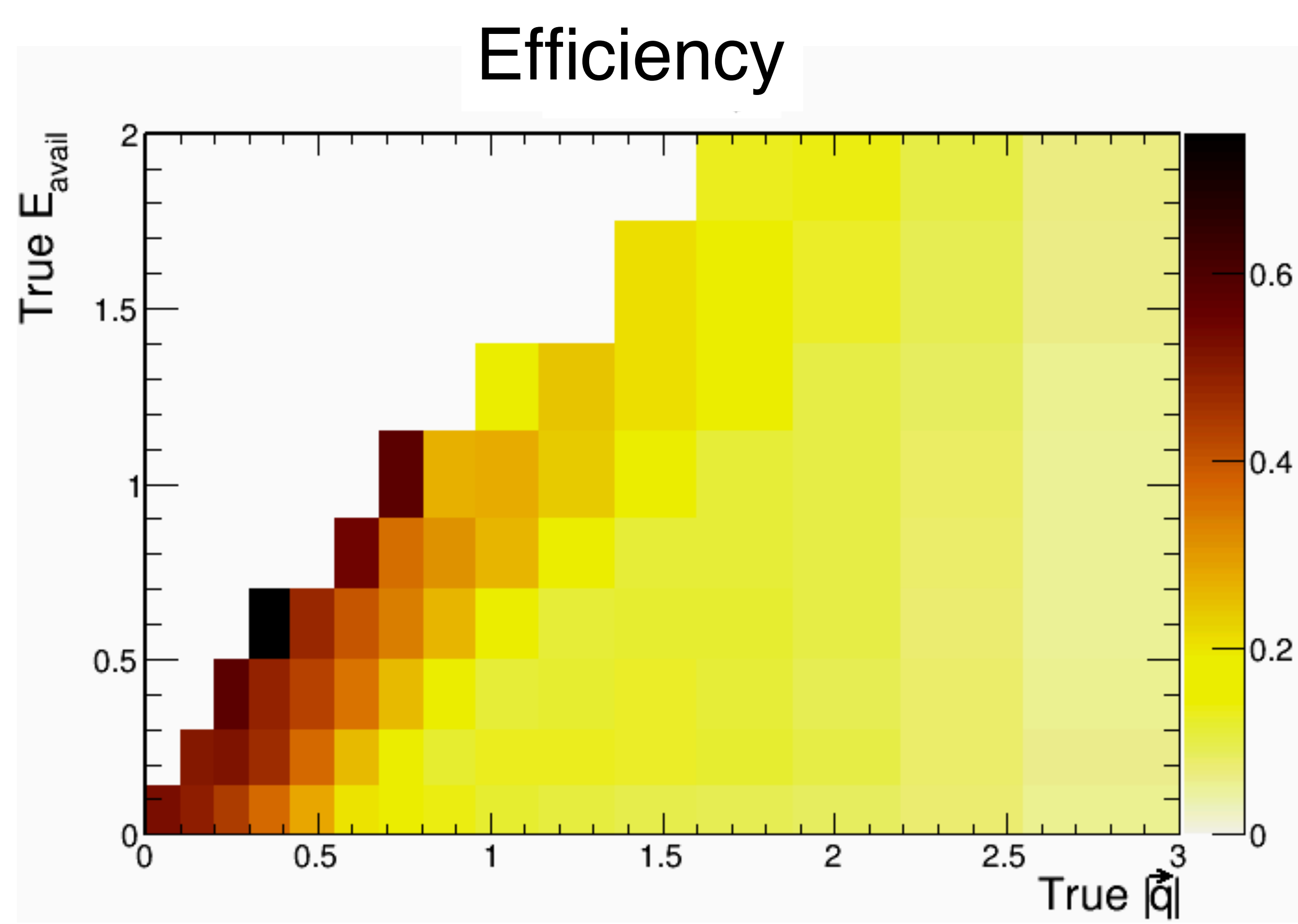
- As other experiments, NOvA also observes an excess of the data respect to the simulation which indicates the presence of a 2p2h process.



Measuring 2p2h

- Most of the 2p2h events according to the Empirical MEC model are in $E_{avail} < 0.6$ GeV and $|\vec{q}| < 1.2$ GeV in NOvA.
- Good opportunity to measured the cross section where 2p2h is expected to be enhanced.





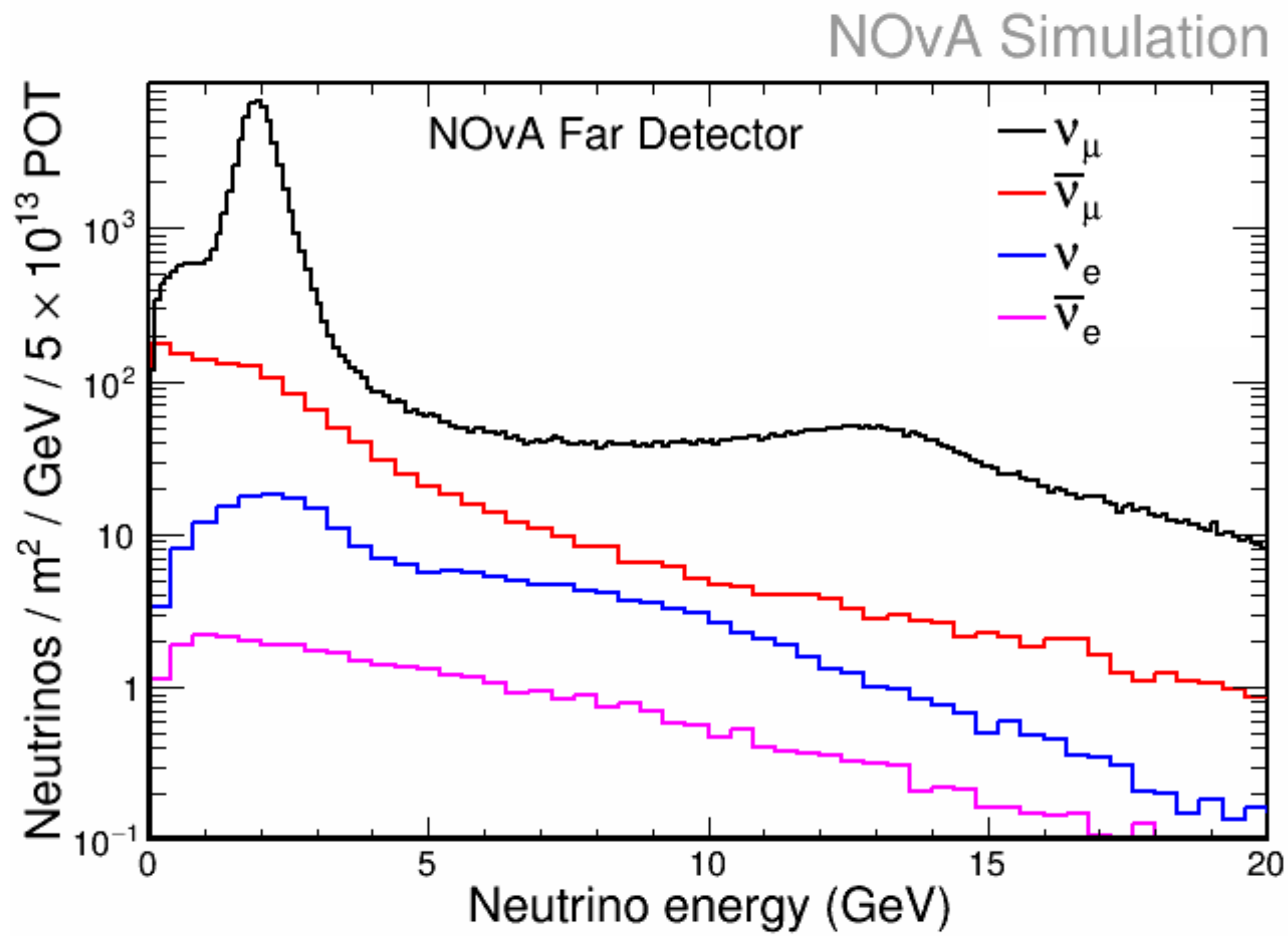
Analysis is initial stage.

ν_e-CC Inclusive

- **Goal: double differential cross sections as function of electron kinematics (E_e, $\cos\theta_e$) which has never been measured before.**

- Signal of ν_e appearance oscillation measurement.

- **Challenge**: ν_e component of the flux is very small.



Event rates in 1-5 GeV:

ν_μ : 96.3%

ν_μ : 2.7%

$\nu_e + \nu_e$: **1.1%**

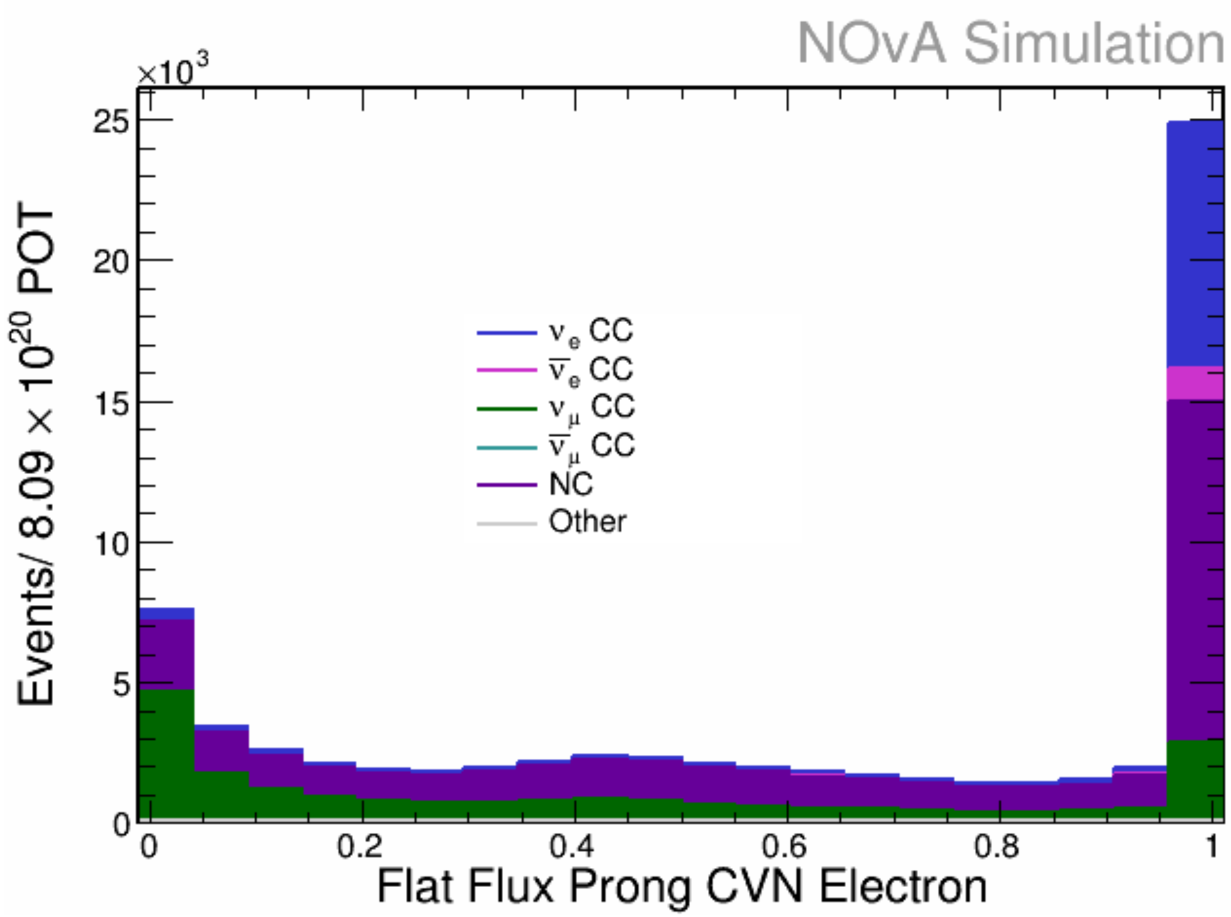
Fermilab

CVN for Particles

- A convolutional visual network (CVN) is trained on single simulated particles drawn from flat kinematic distributions.
  - Prong: reconstructed particle trajectories.
  - Output is called Flat Flux Prong CVN.
- It assigns a score (in [0,1]) for 5 types of particles: μ, p, π^{+-}, γ and e.

Percentage of particles in training

e	γ	μ	π^{+-}	p
20%	20%	20%	20%	20%

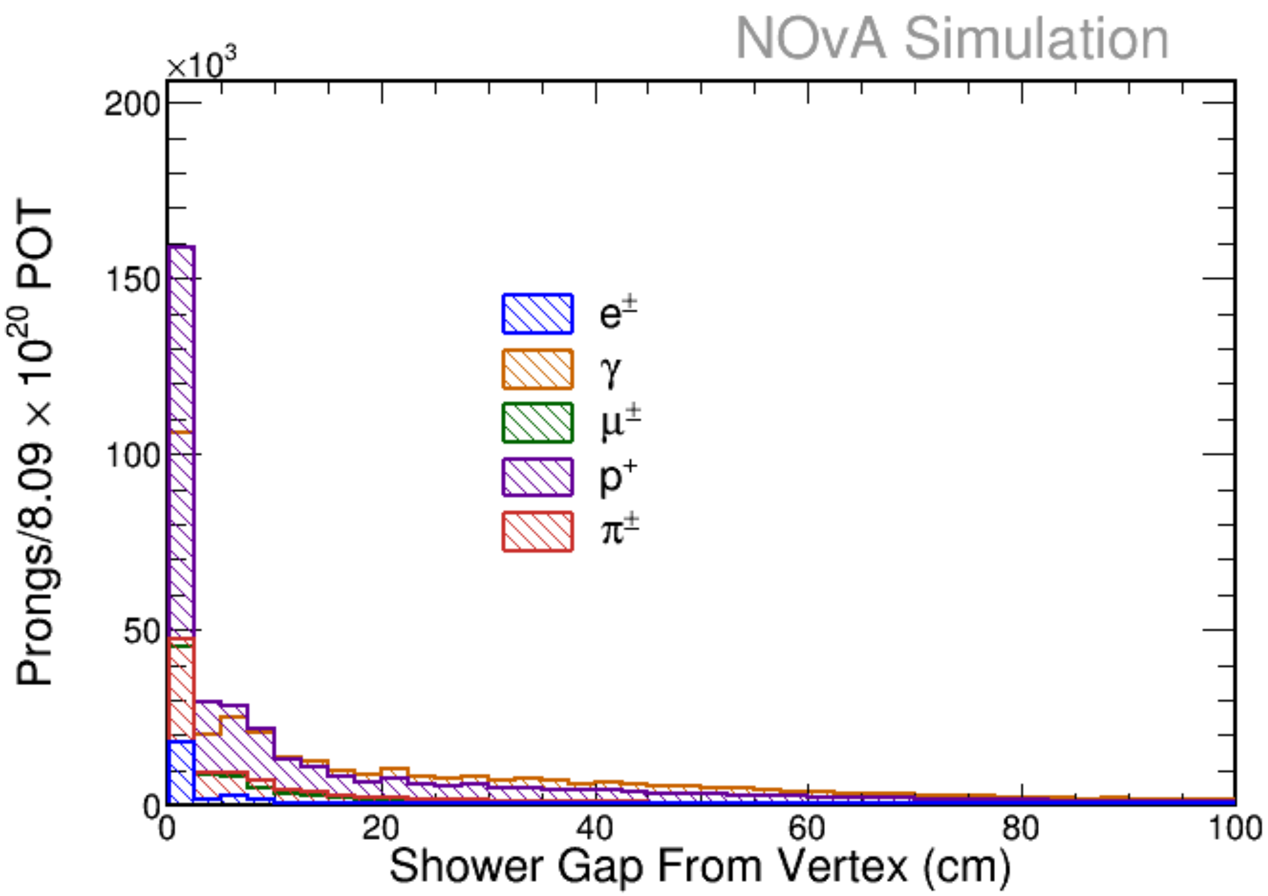


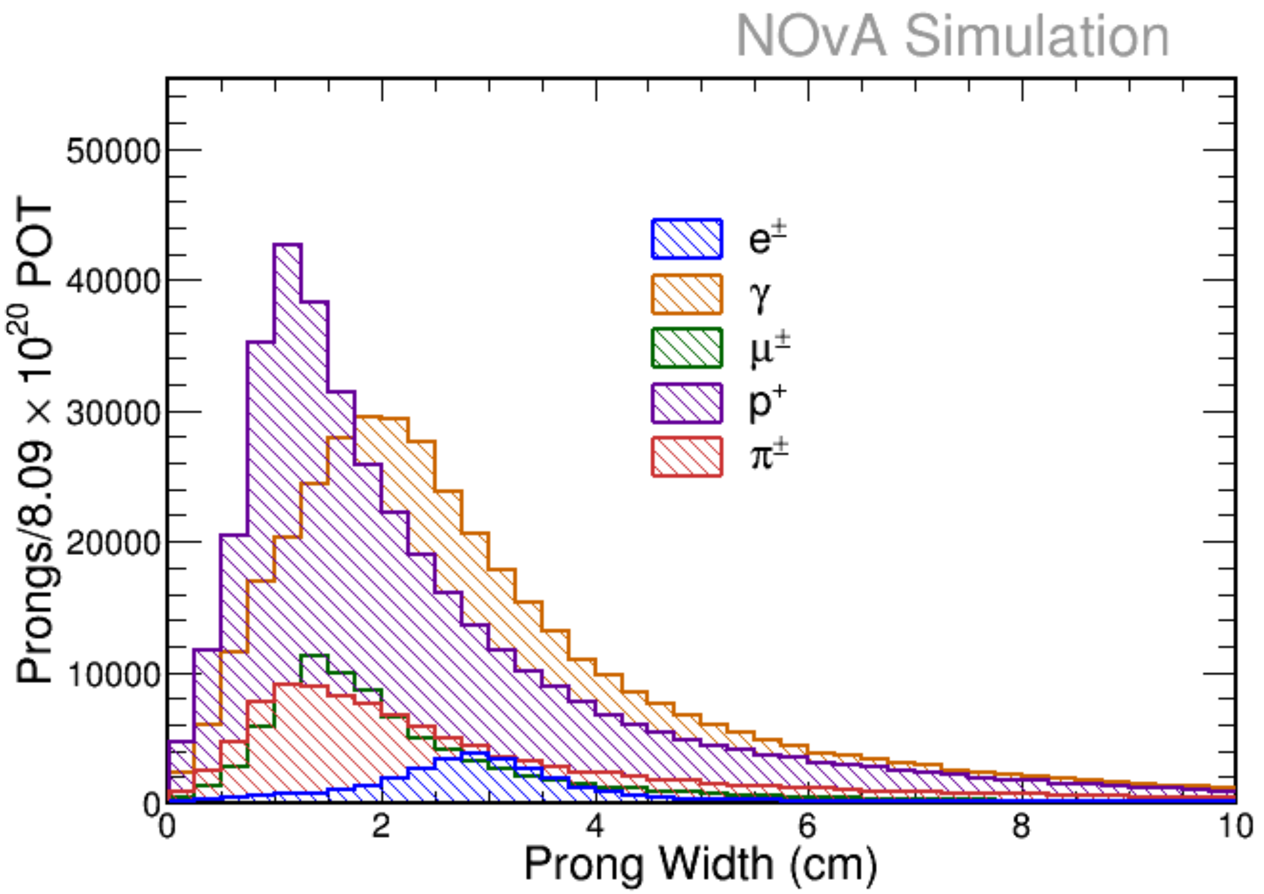
Electron ID

- A BDT was trained to add additional event level information to machine learning results:
  - Flat Flux Prong CVN.

    +

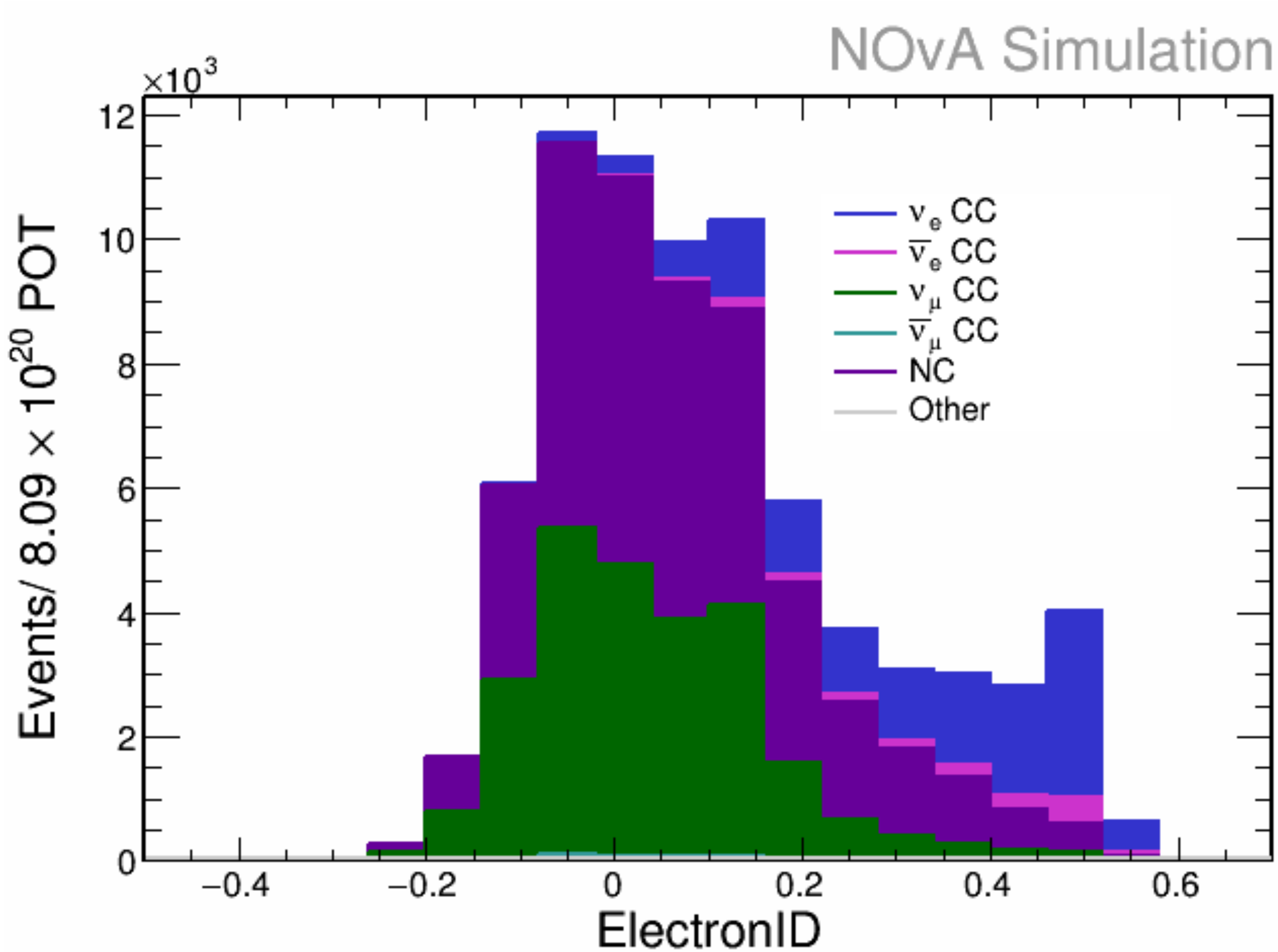
  - Shower gap from vertex.
  - Prong width.





Electron ID

- Overwhelming background from ν_μ-CC and NC.



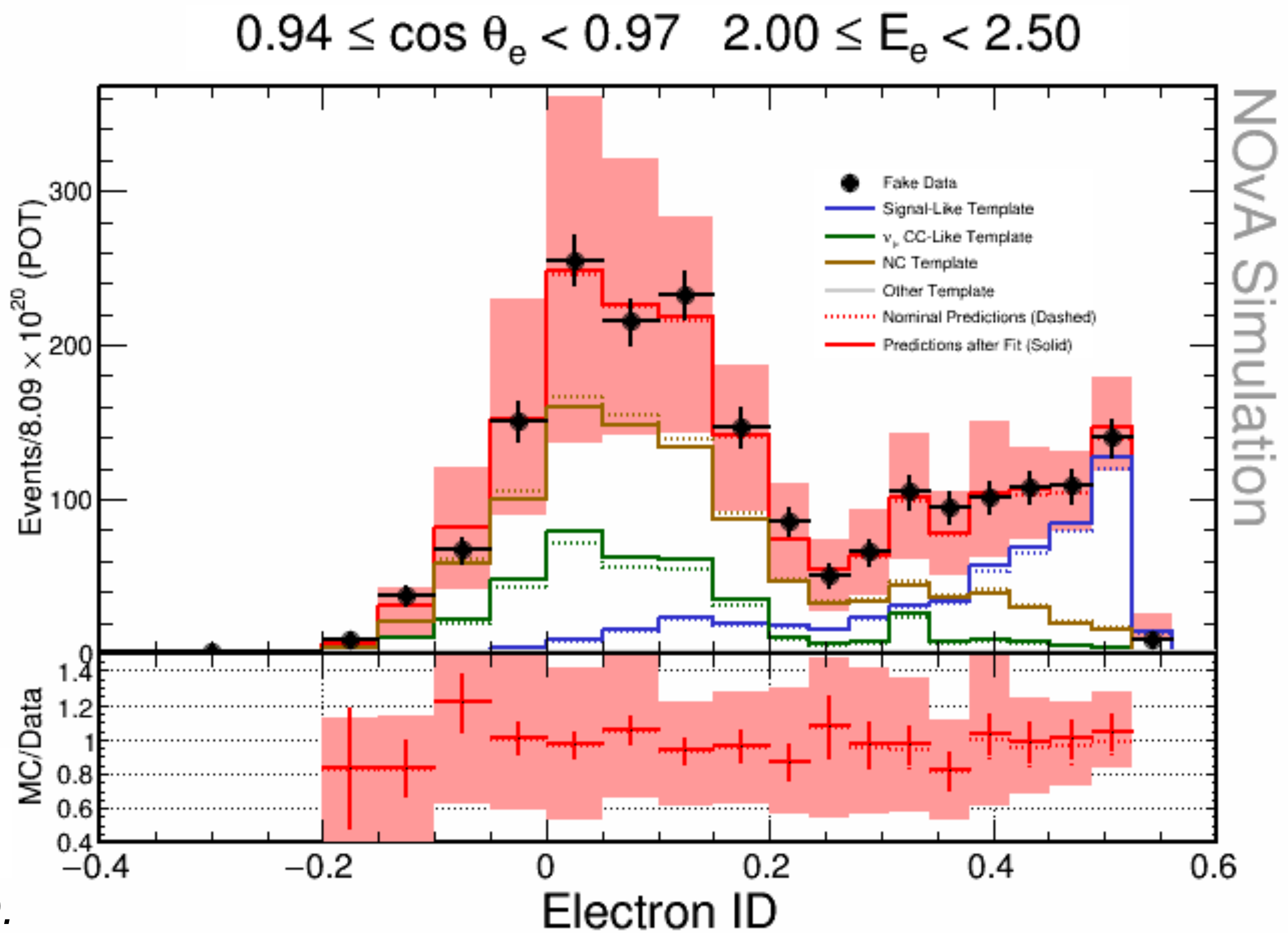
Template fit

- Uses a data driven technique to extract signal and background estimates.
- PID template is generated and fit to data in each analysis bin.
- Template:
  - Signal
  - ν_μ-CC
  - NC
- A covariance matrix is used to account for uncertainties in template shape and normalization

Fit my minimizing:

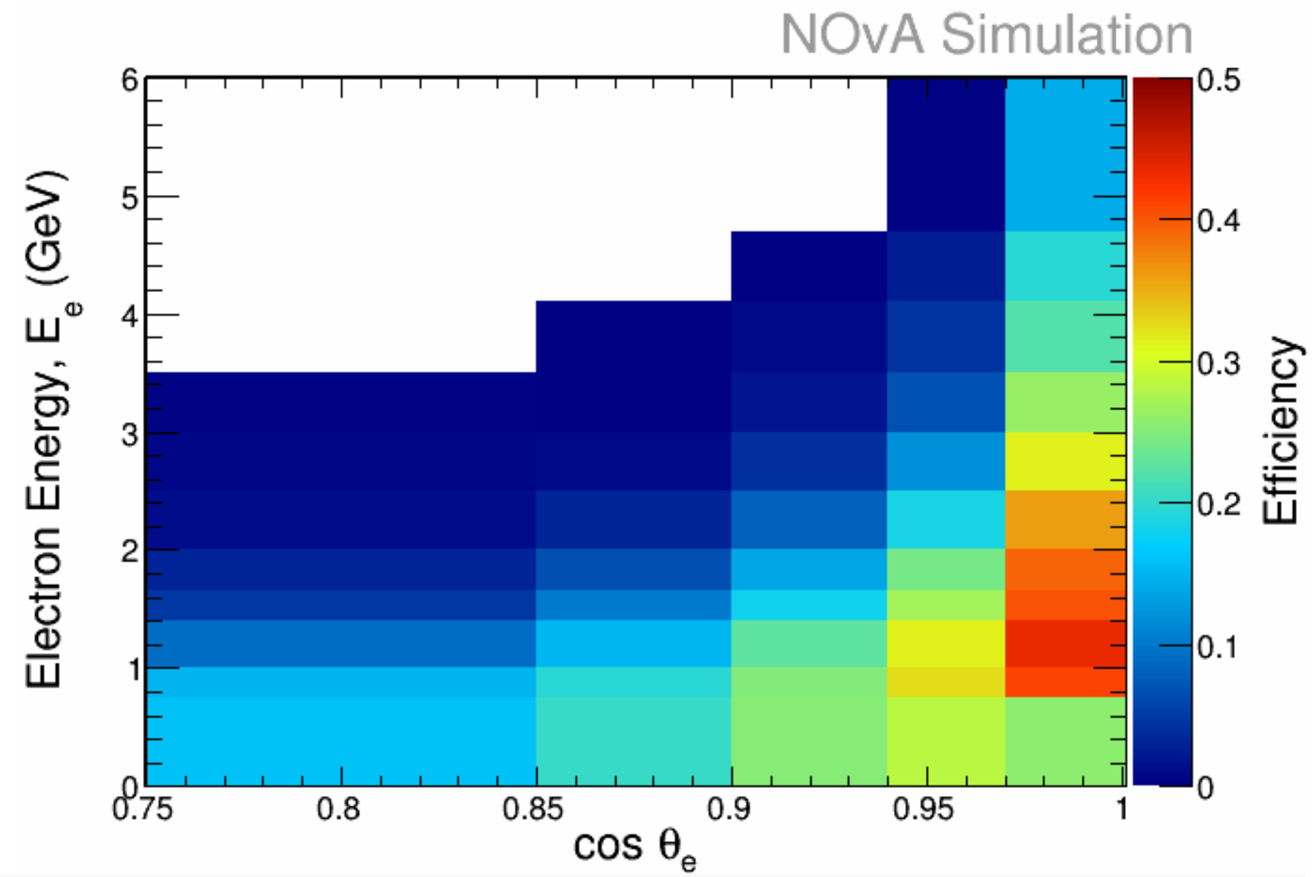
$$\chi^2 = (x_i - \mu_i)^T V_{ij}^{-1} (x_j - \mu_j)$$

(x: data, V: covariance, μ: prediction).

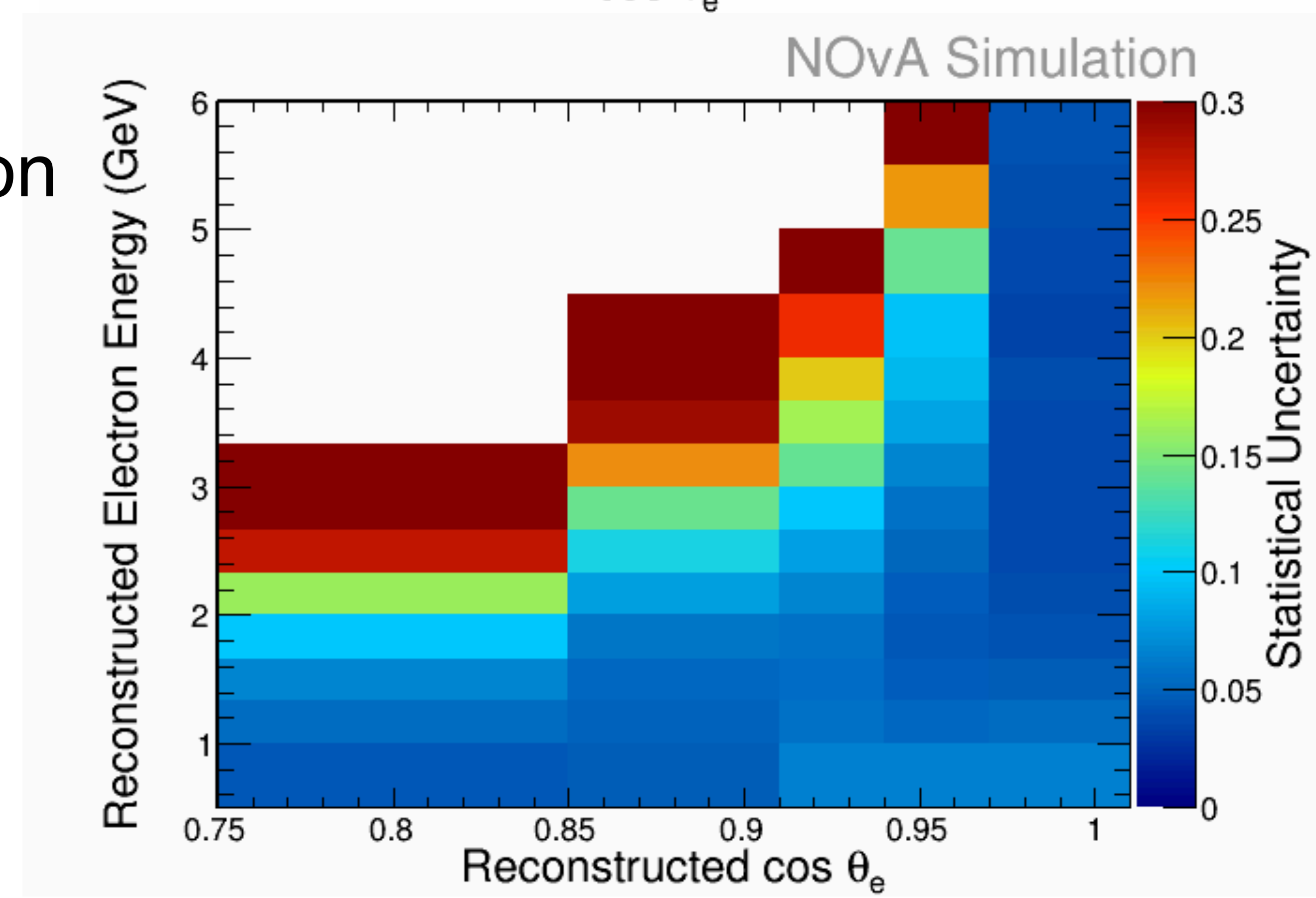


Results coming soon…

- Good signal **efficiency** thanks to Electron ID and the template fit method.



- **Statistics** allow for the first double differential ν_e- CC inclusive cross-section measurement in this energy range.



- Expecting measurements with ~15% systematic uncertainties.

Analysis is in final stage… expect a publication soon!

Semi-inclusive Analysis Progress Using the ν_μ-CC Inclusive Sample

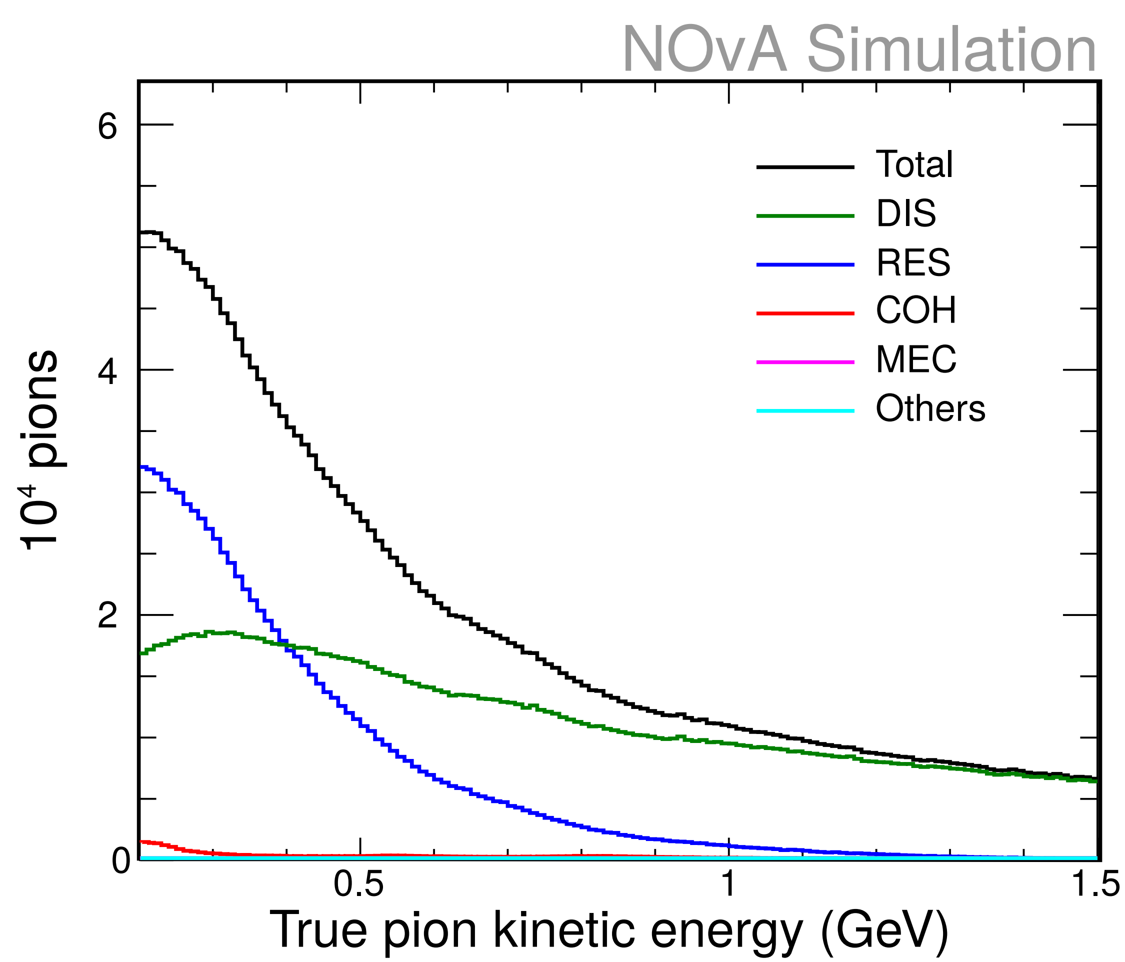
- ν_μ-CC π^{+-}
- $\bar{\nu}_\mu$-CC π^0
- ν_μ-CC 0π

ν_μ-CC Charged Pion: $\nu_\mu + A \rightarrow \mu^- + \pi^{+-} + X$

- **Goal: cross section respect to the pion kinetic energy.**

  -> one muon track and at least one charged pion track ($E_\pi \geq 350$ MeV).

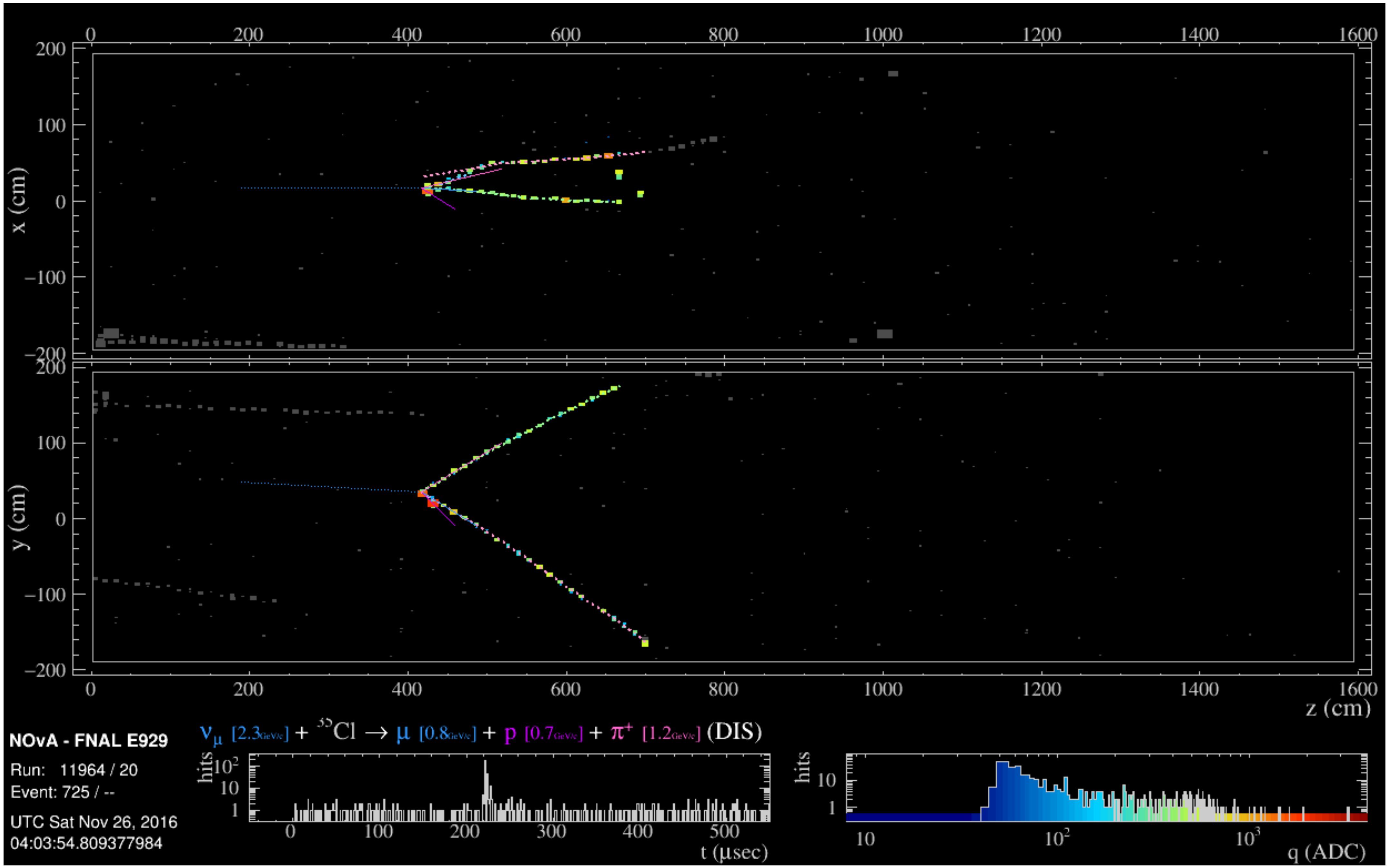
- Same optimized cuts as the ν_μ-CC inclusive analysis.



Fermilab

Charged Pions at NOvA ND

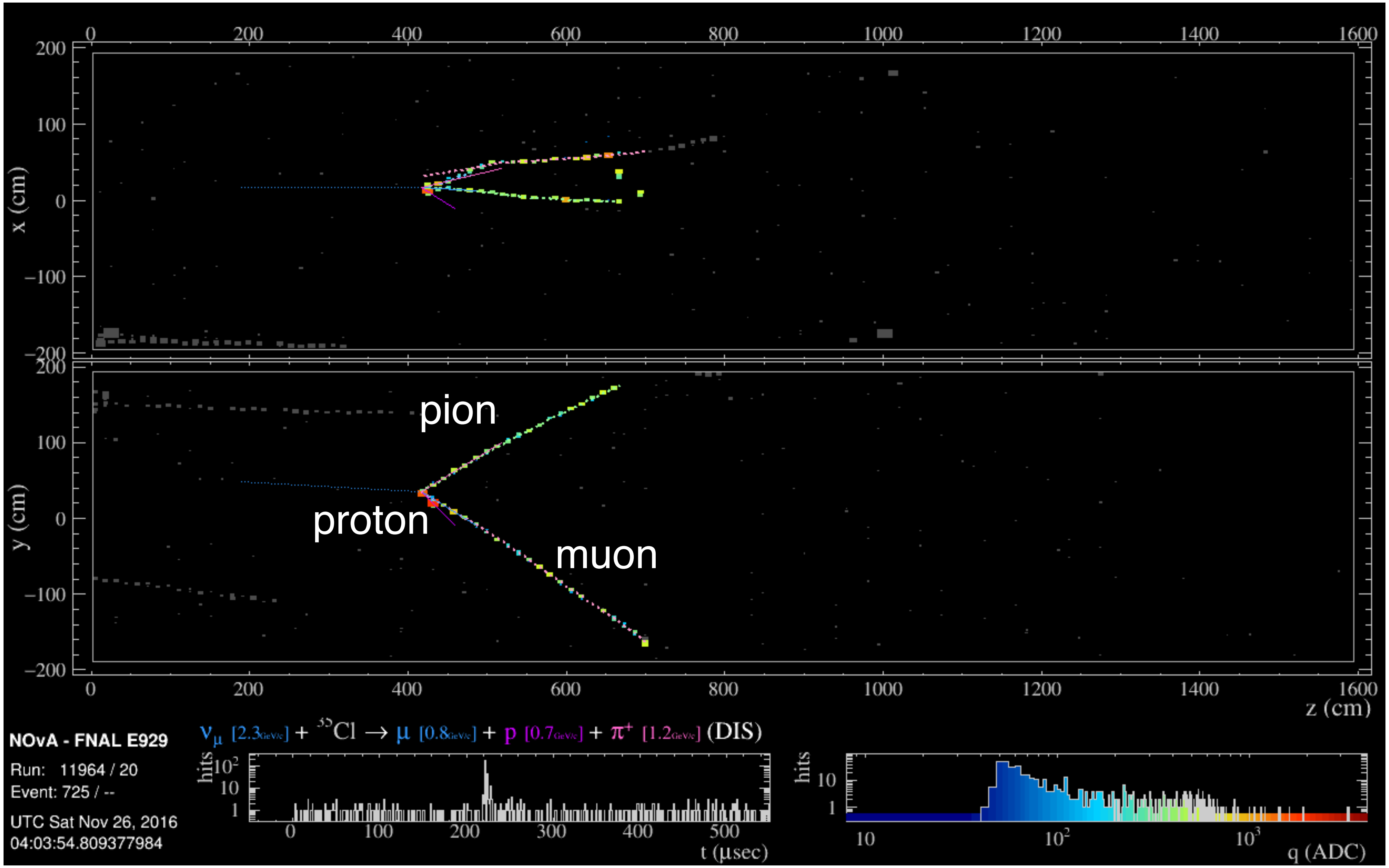
- Event from MC:



Fermilab

Charged Pions at NOvA ND

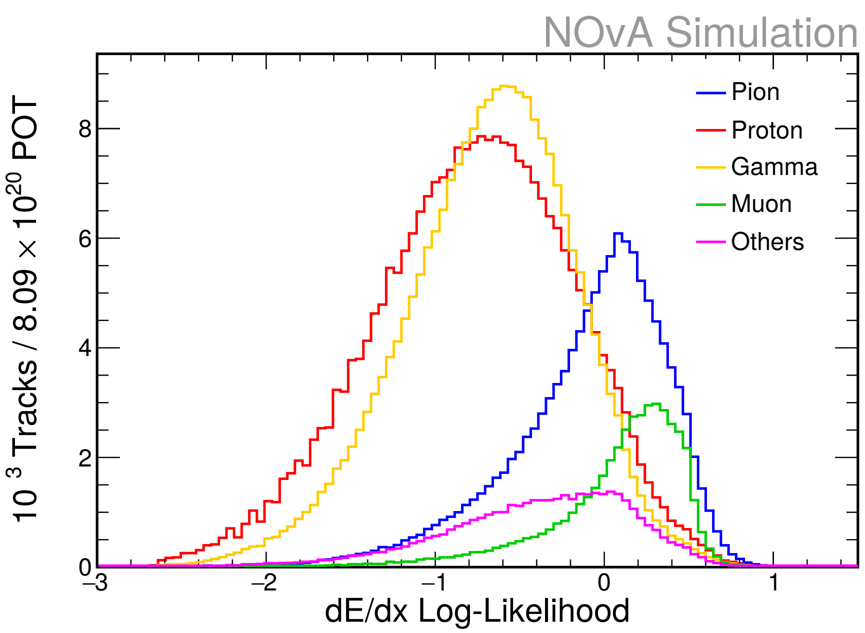
- The challenge is to identify pions between protons, muons and gammas.

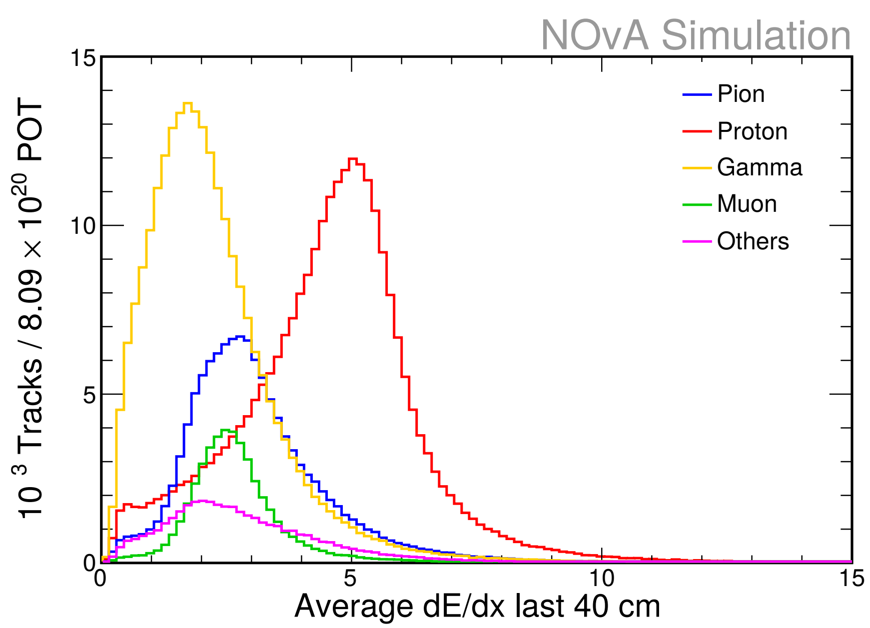


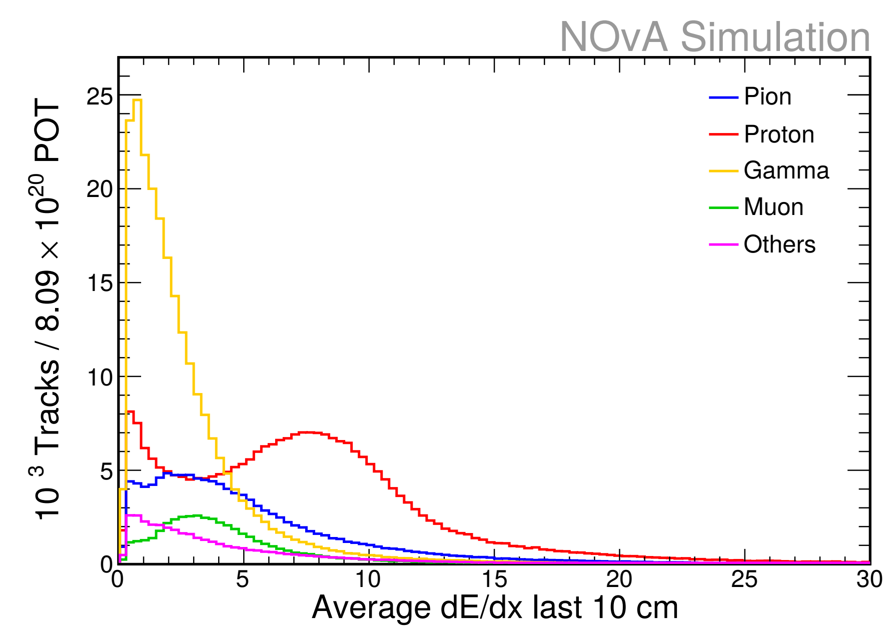
Fermilab

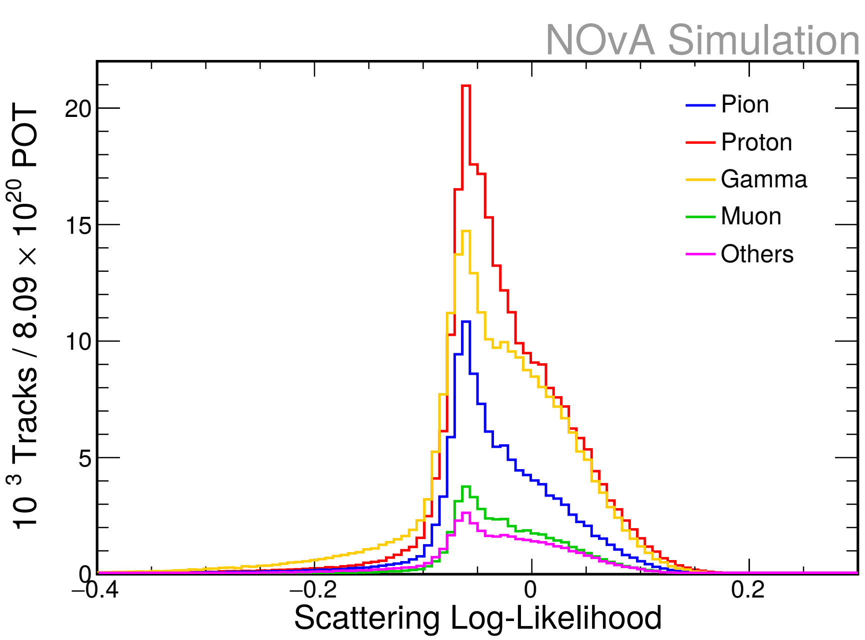
Discriminating Variables

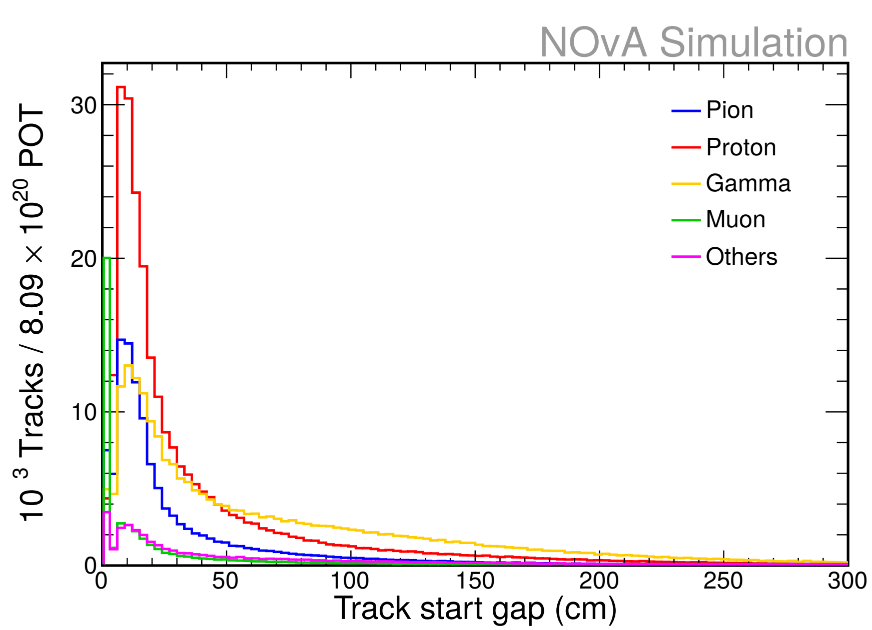
- 6 discriminating variables for BDT:
  - energy loss and scattering difference.
  - gap density and track start gap discriminate against gammas.

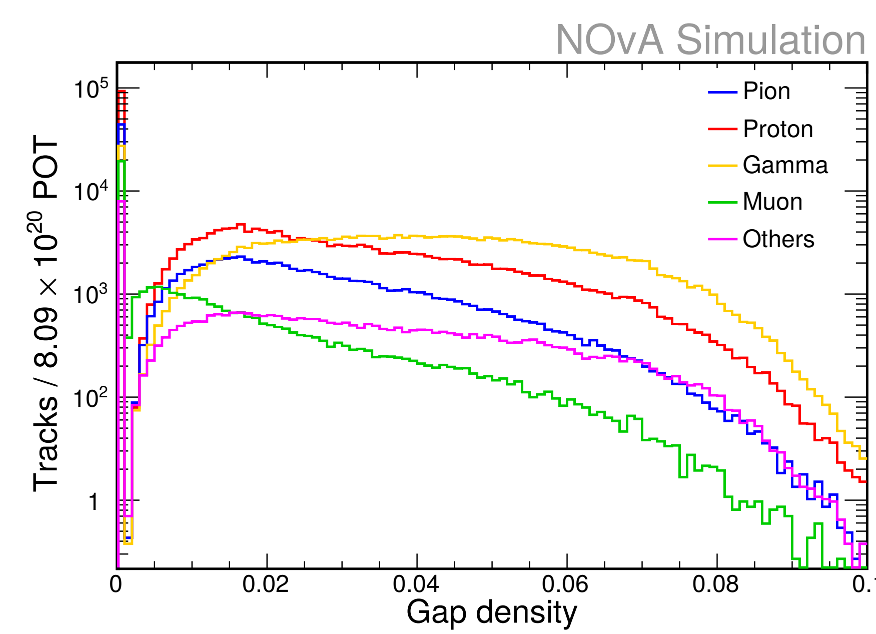






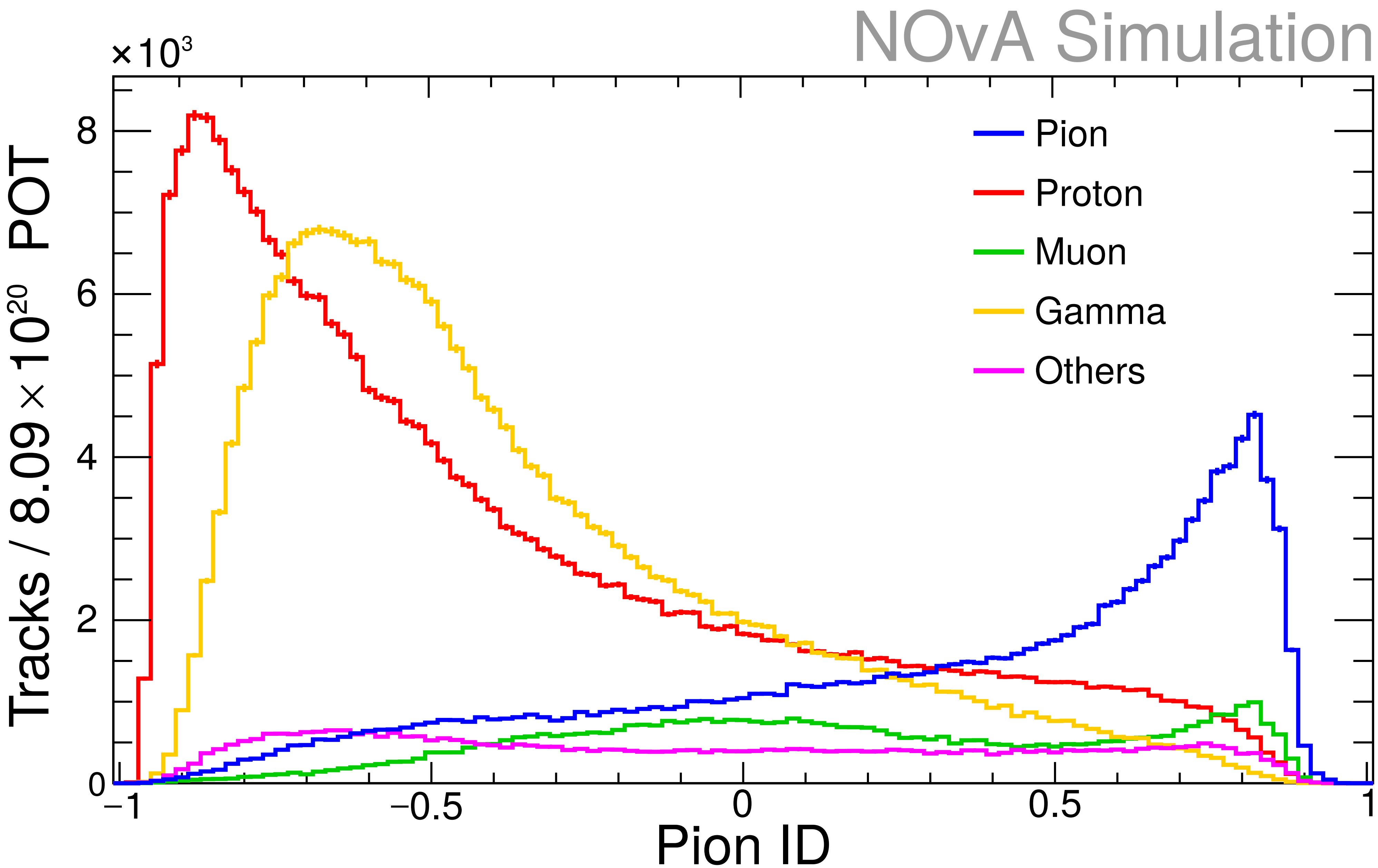






Pion BDT score distribution

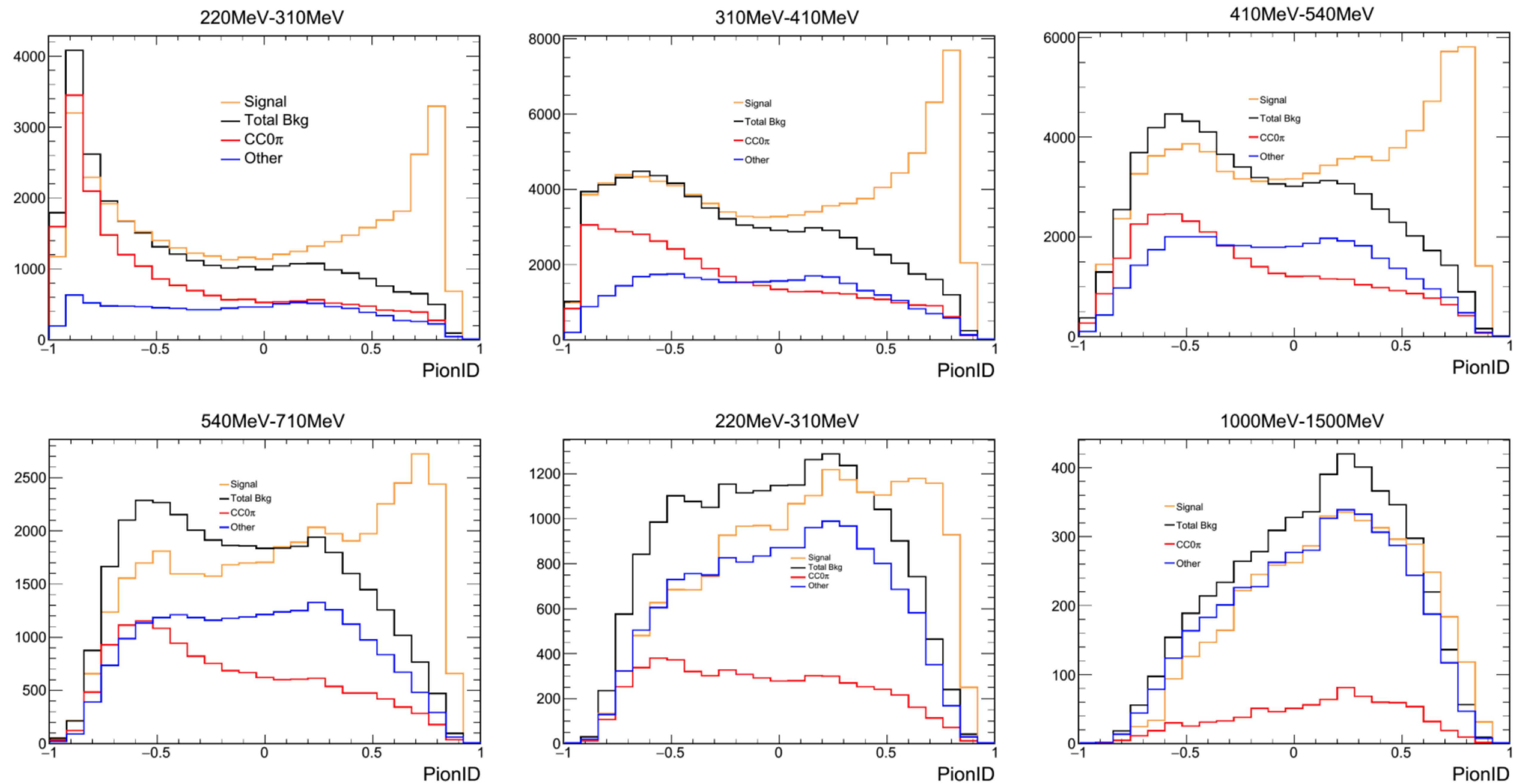
- Pion score distribution for different particle types (max Pion ID in the event):



- Even for higher Pion ID values there are many proton, muons and gammas that can be mis-identified as pions.

Template Fit

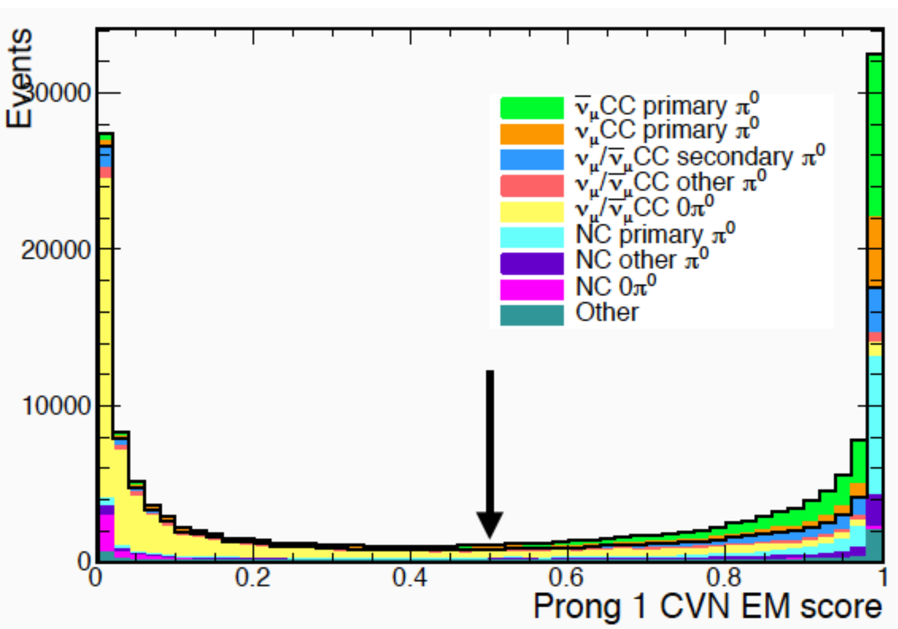
- This analysis uses template fits in the pion energy bins respect to the PionID. Template: signal, CC-ν_μ 0π and others.

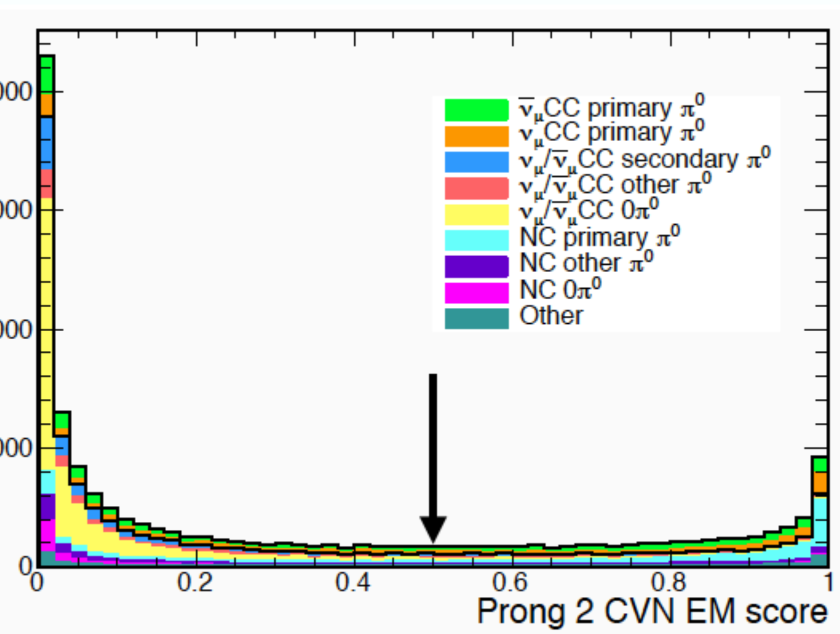


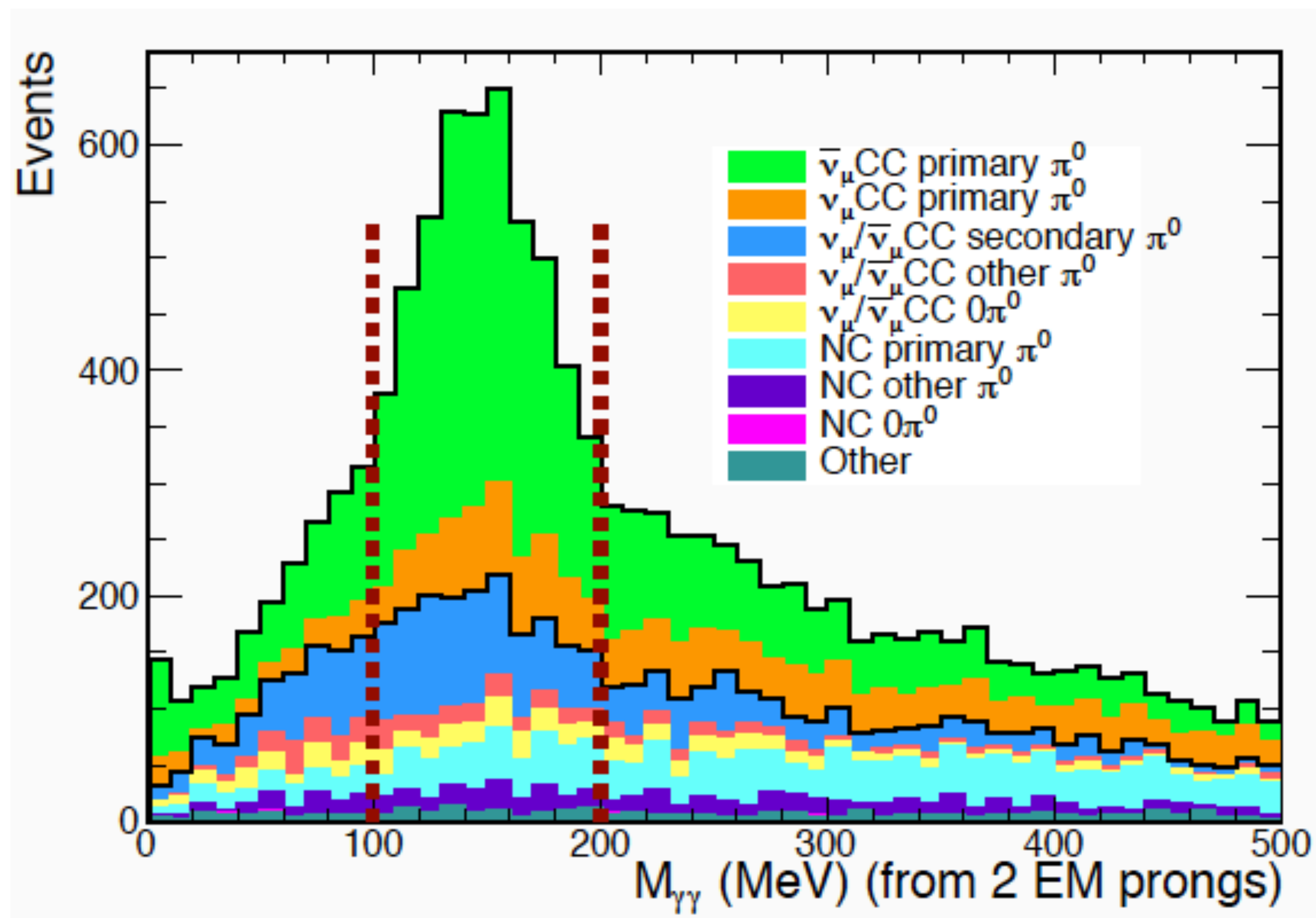
Work in its first stage.

$\overline{\nu}_\mu$-CC Neutral Pion

- **Goal: cross section with at least 1 primary π^0.**
  - Same optimized cuts as the νμ CC inclusive analysis.
  - Reconstructed Tμ > 0.4 GeV.
- Progress toward a Pi0 ID: 2 gammas identified using Flat Flux CVN.

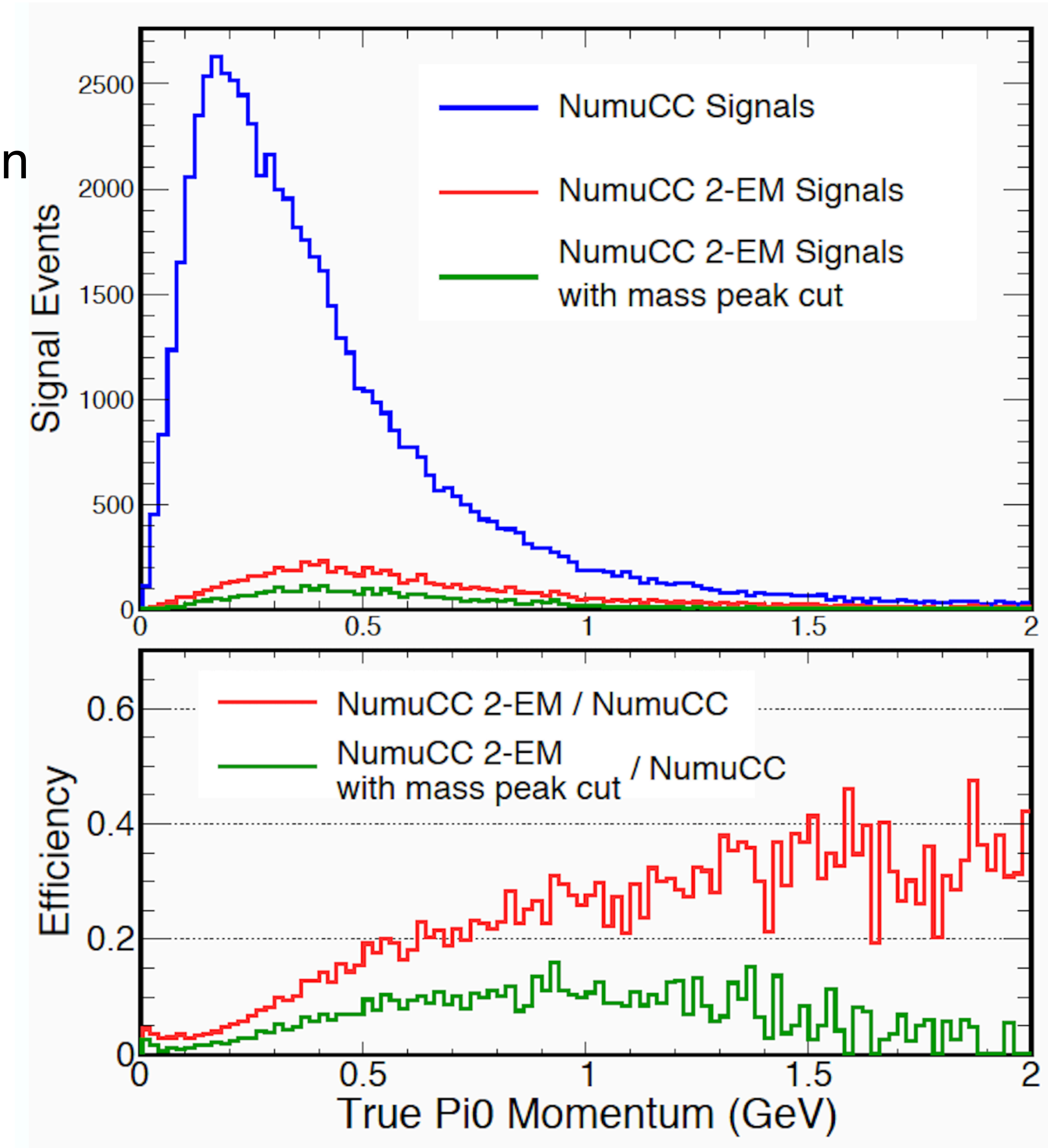






Efficiency

- Efficiency of the signal selection using 2-EM CVN > 0.5



True signal

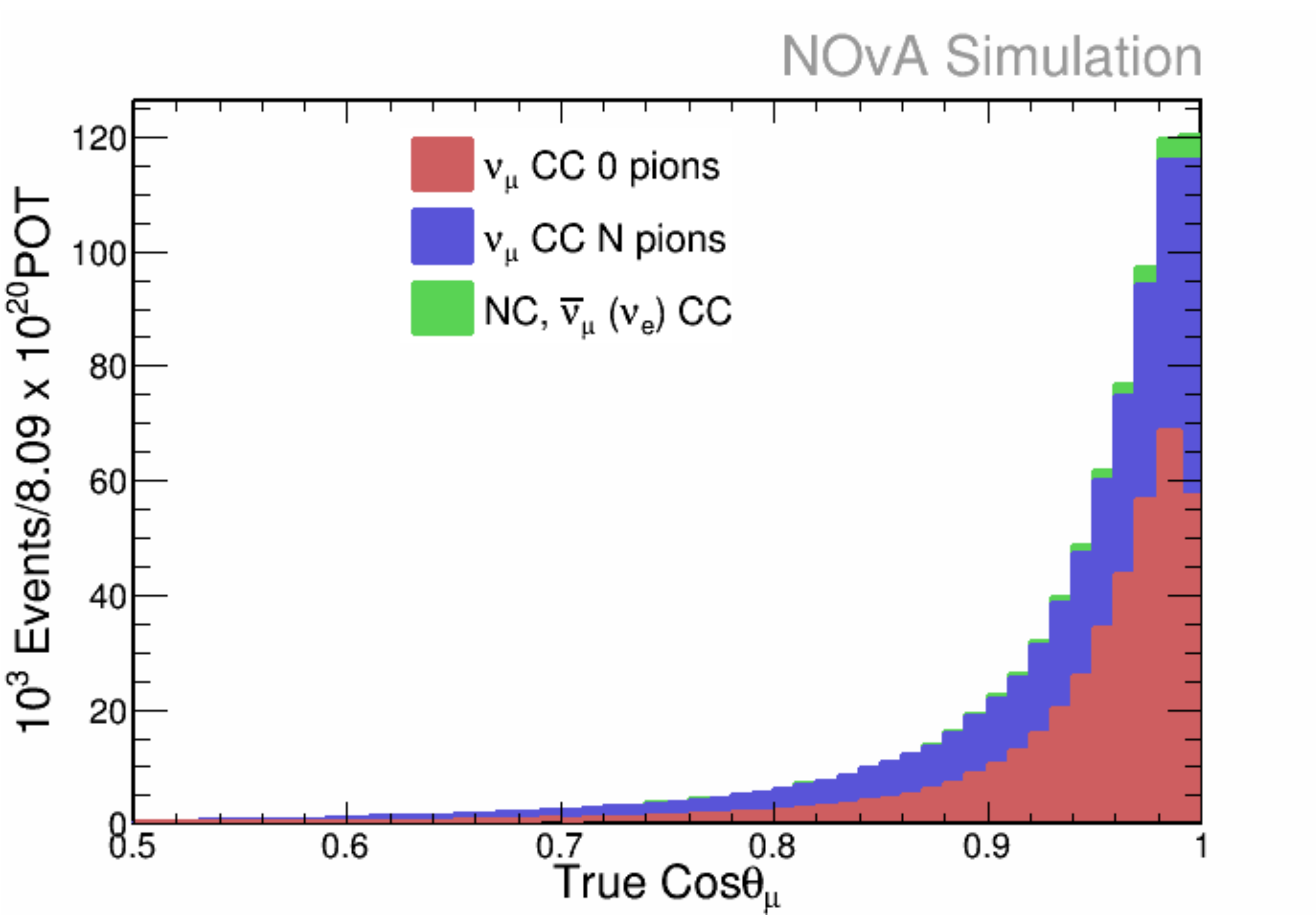
No m_{π^0} peak cut.

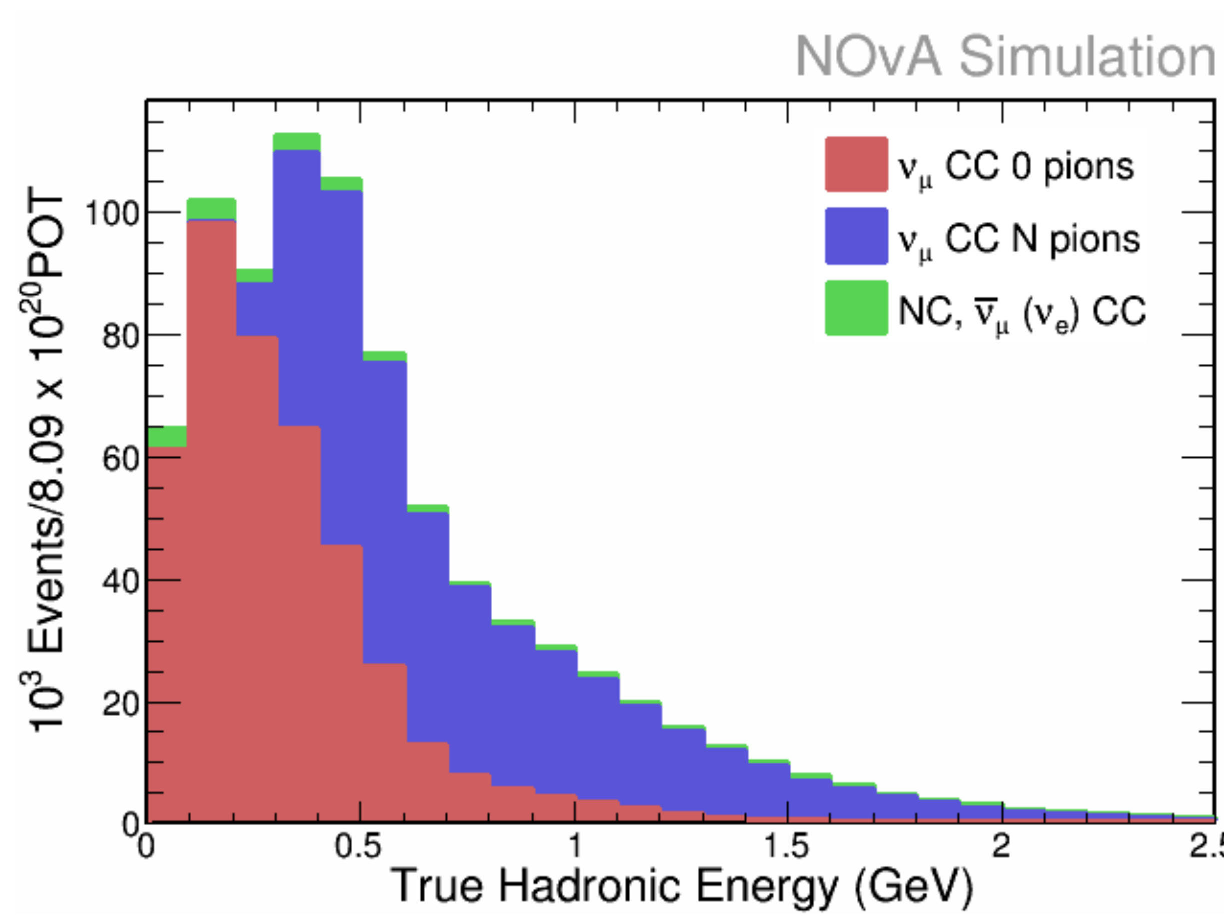
$100 < m_{\pi^0} < 200$ GeV peak cut.

Work in its first stage.

ν_μ-CC Pionless

- **Goal: cross section respect to muon kinematics. We will also explore dependency of proton multiplicity and single transverse variables.**
- Starting point: the ν_μ-CC inclusive sample. Distributions after ν_μ-CC selection:





Work in its first stage.

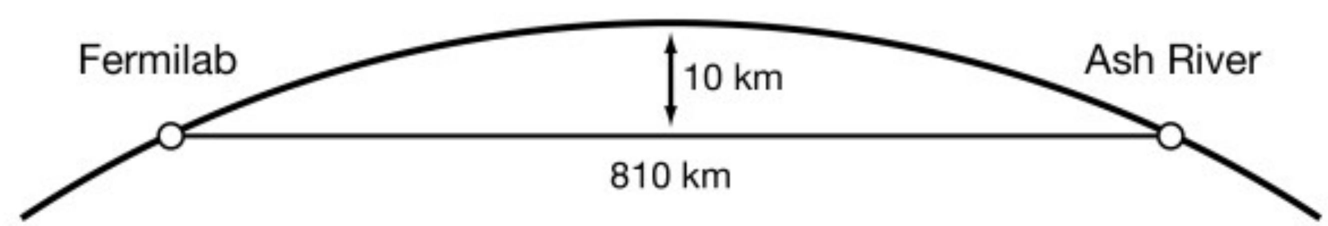
Conclusions

- The NOvA experiment has an excellent opportunity to make a high precision neutrino-nucleus cross section measurements for both, FHC and RHC.
- We already have presented results for the CC semi-inclusive neutral pion and the NC coherent neutral pion cross sections that will be published soon.
- The CC inclusive channels have the highest priority now and they are in the last stages of Collaboration review.
- Other analyses will follow soon. **Stay tuned!**

Backup

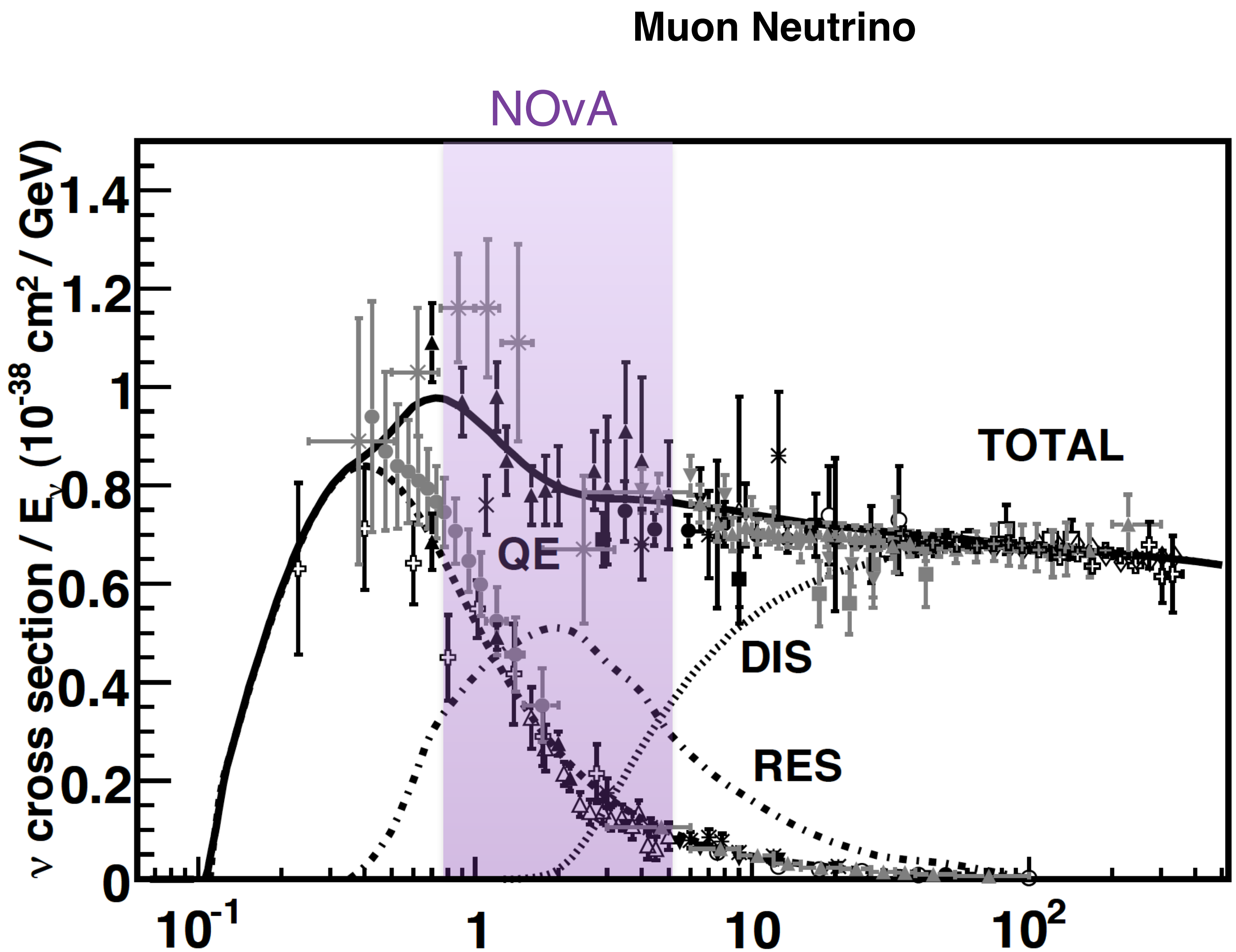
The NOvA Experiment

- NOvA is a long baseline oscillation experiment to measure:
  - Mixing angle Θ_{23}.
  - CP-violating phase.
  - Mass hierarchy determination.



- The ND provides an excellent opportunity to measure neutrino interaction cross sections with high statistics.

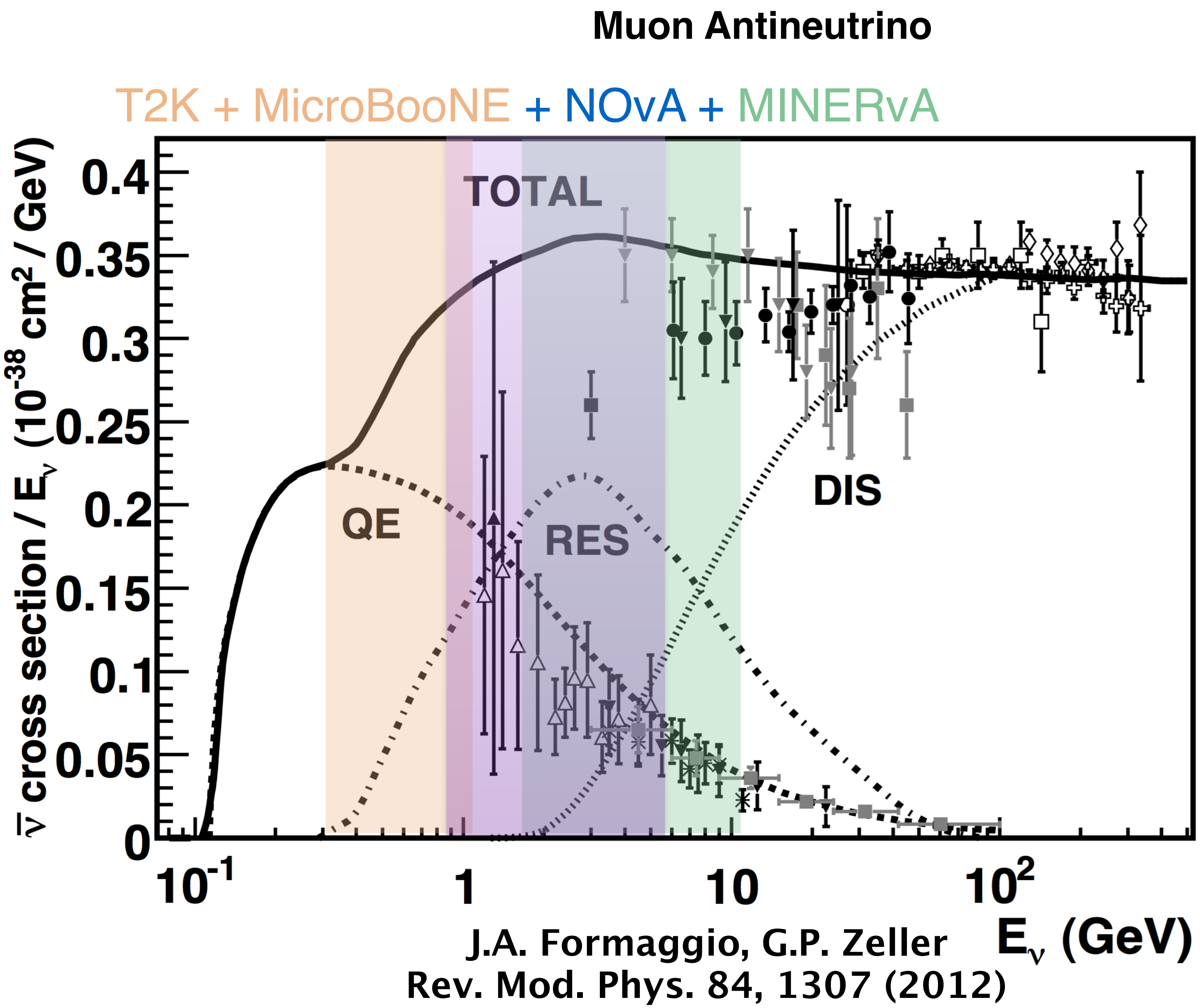
NuMI Beam at NOvA



J.A. Formaggio, G.P. Zeller
Rev. Mod. Phys. 84, 1307 (2012)

- Even with a narrow band beam, NOvA is still sensitive to many different nu+A interaction channels.
- High data rate at the ND.
- Protons on target:
  - 8.09×10^{20} in the FHC mode.
  - Currently 6.26×10^{20} in the RHC mode.

NuMI Beam at NOvA

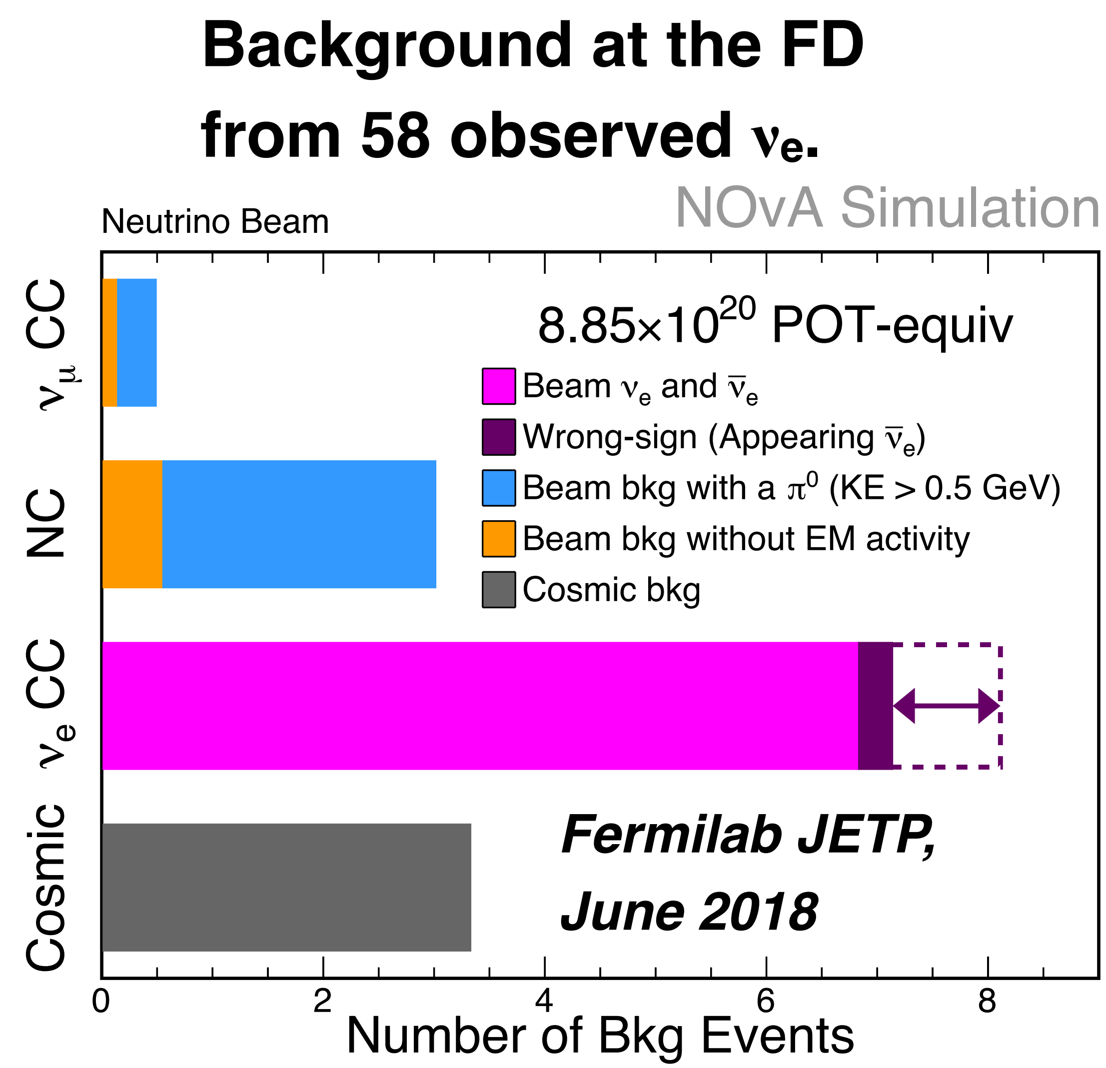


- Even with a narrow band beam, NOvA is still sensitive to many different nu+A interaction channels.
- High data rate at the ND.
- Protons on target:
  - 8.09 x 10^{20} in the FHC mode.
  - Currently 6.26 x 10^{20} in the RHC mode.

π^0 at the NOvA Near Detector

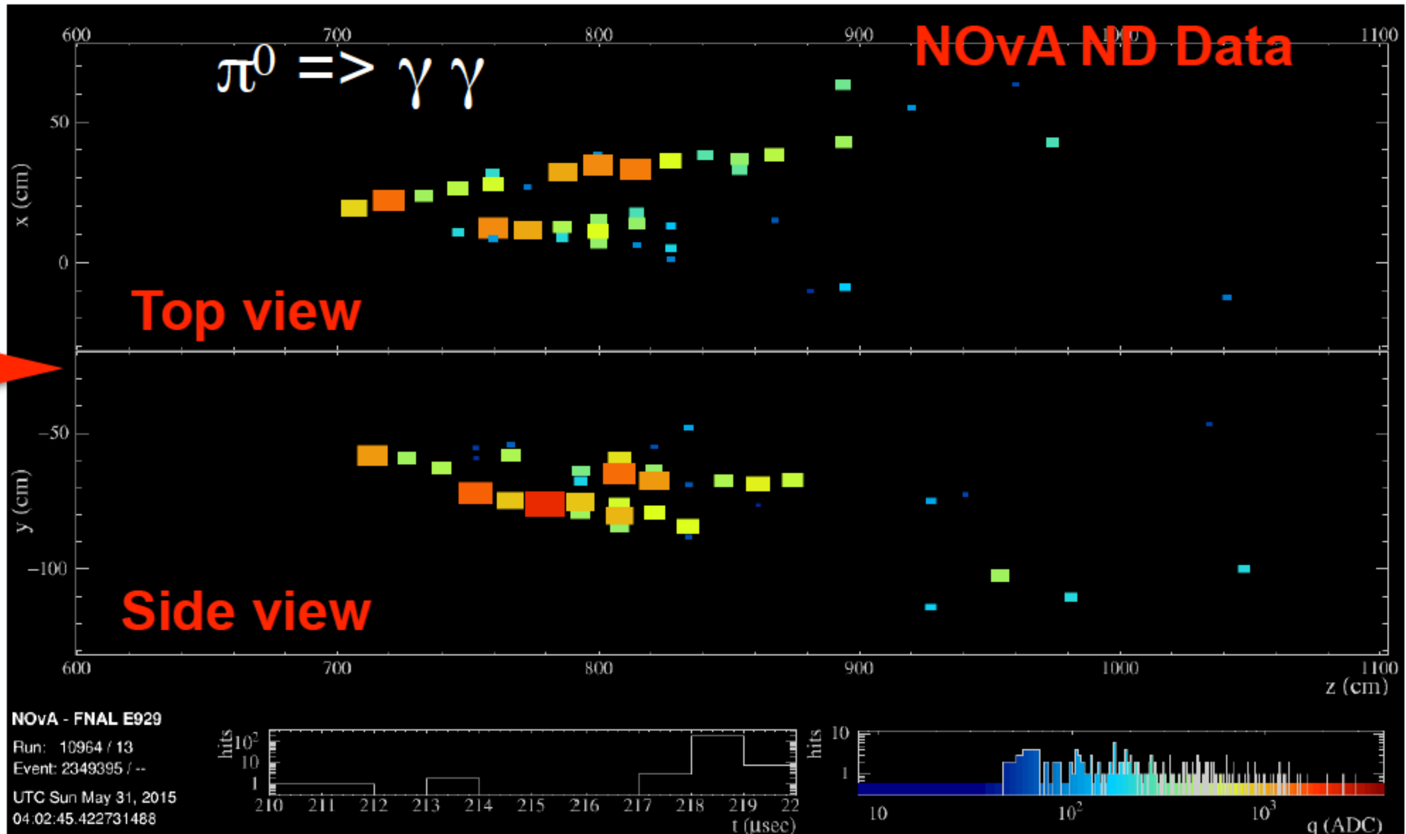
- π^0s are one of the most important background to ν_e appearance oscillation analysis:

  We want to measure them in our own detector!



- Photons from π^0 decay make EM shower.

Beam

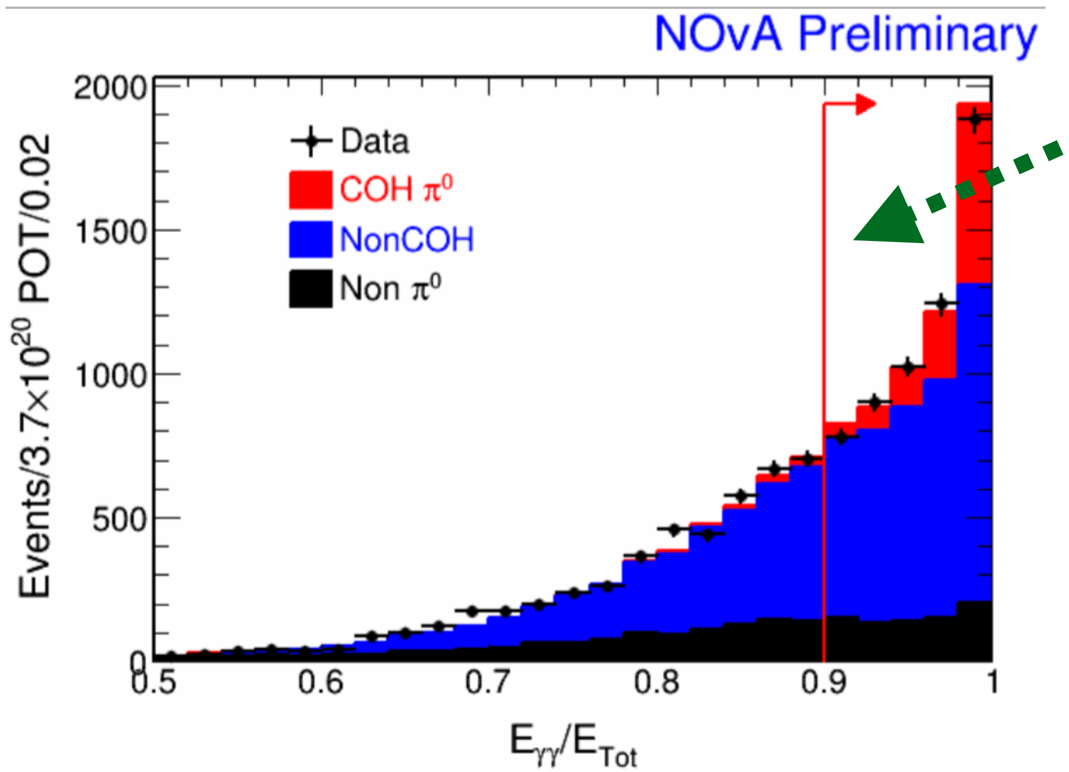


- Pion kinematics are sensitive to FSI:

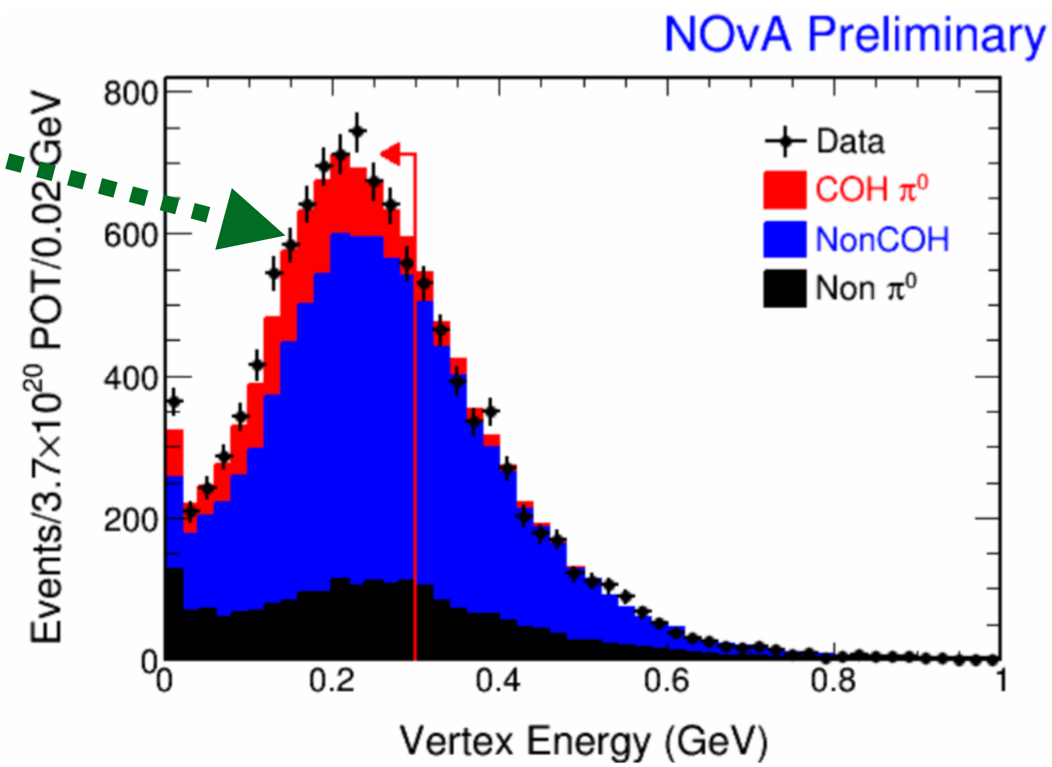
  (in)elastic scattering, absorption, charge-exchange

NC Coherent Neutral Pion: Background Constraint

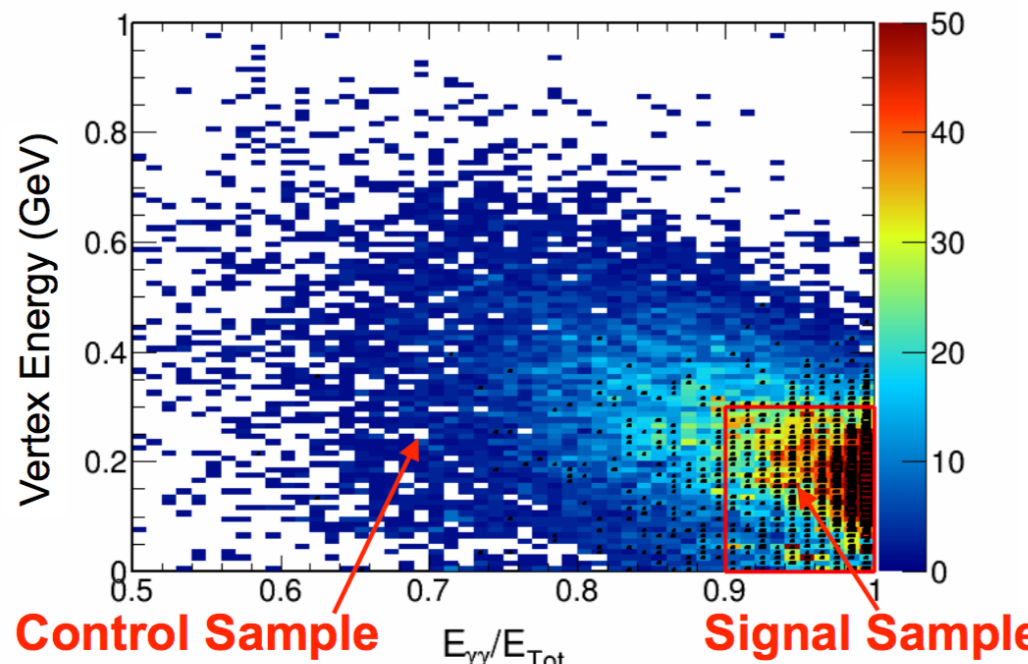
- Background constraint based on control and signal region



Signal region: almost 90% of the signal

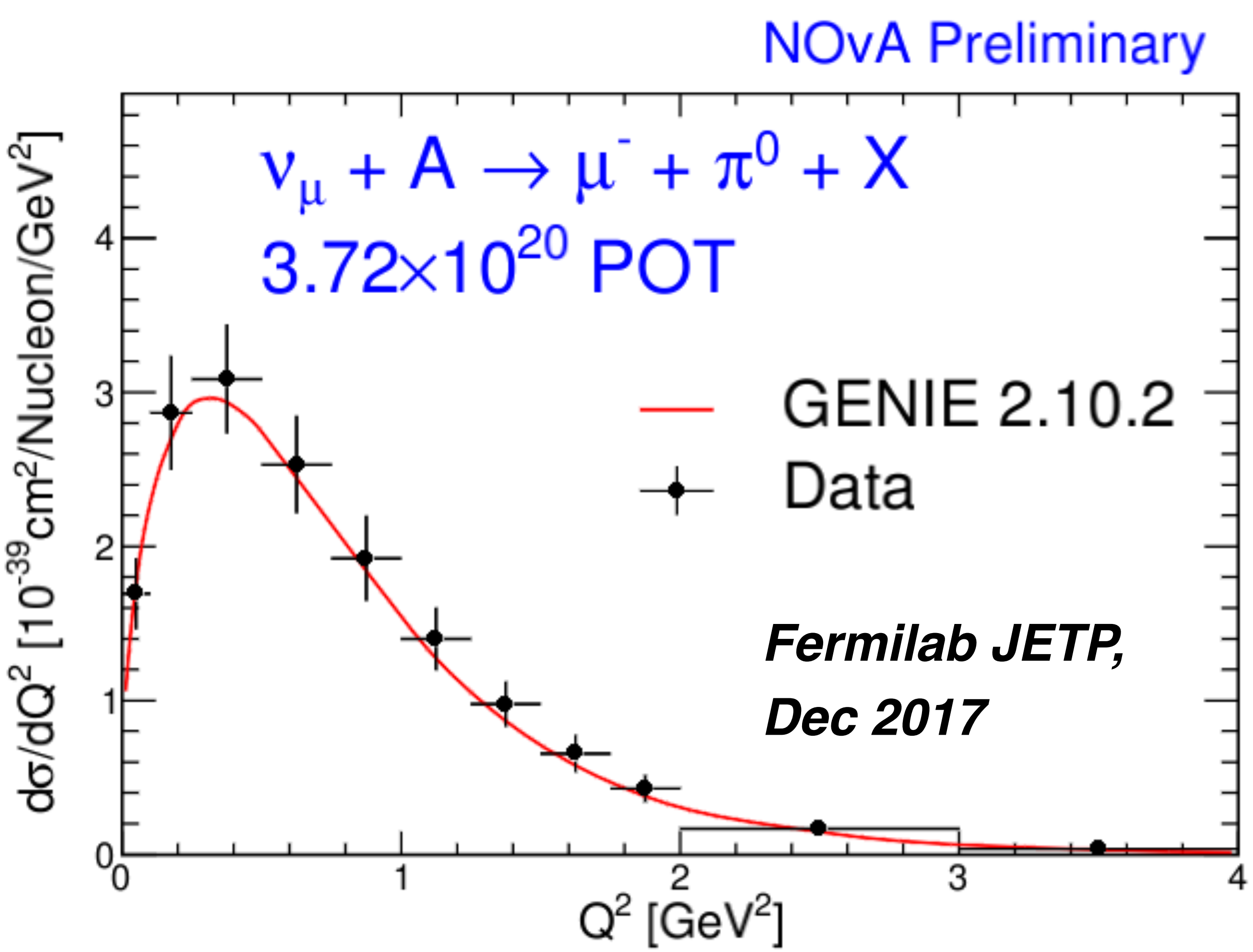


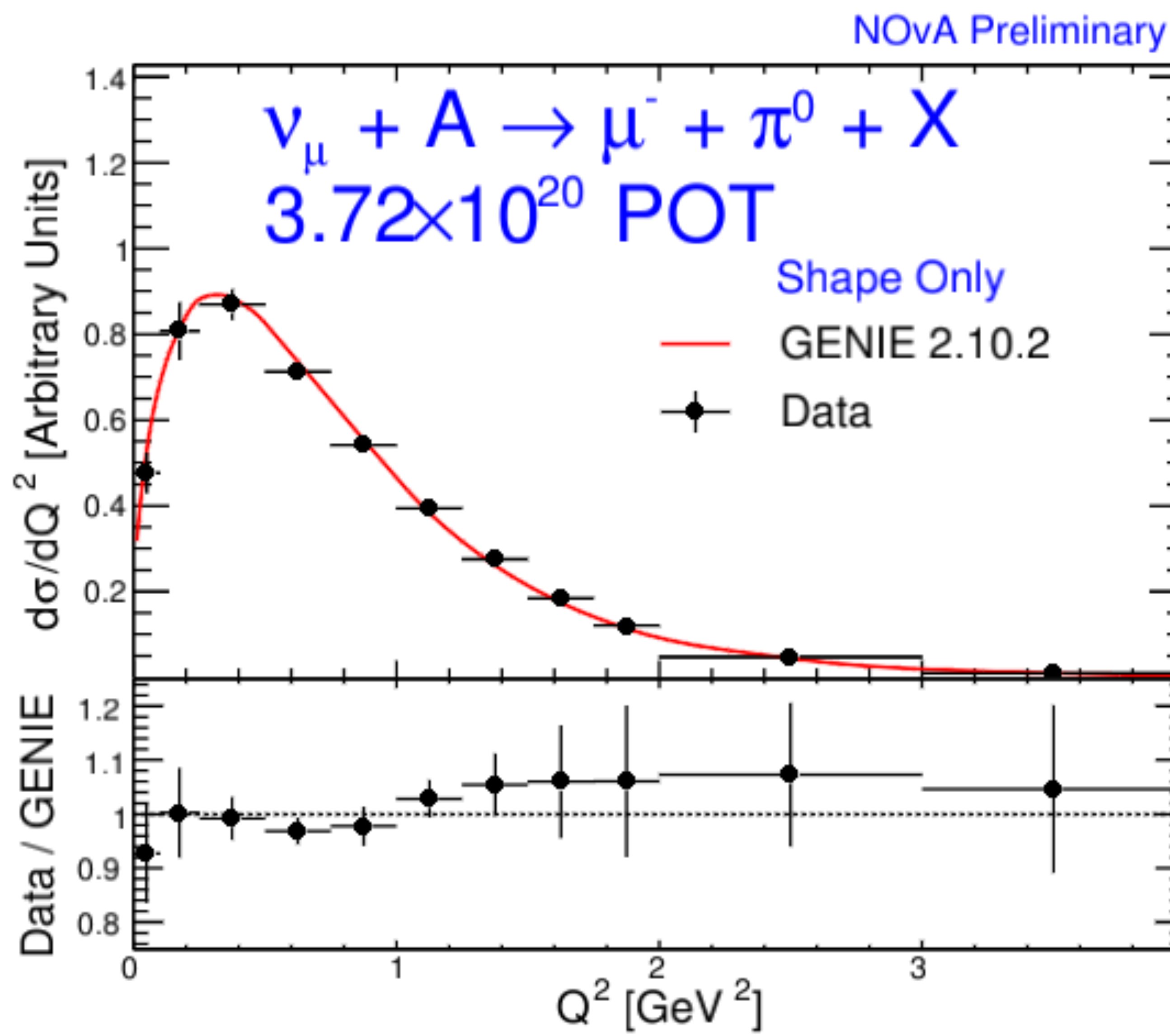
Fit the backgrounds to control sample data in π^0 energy vs angle 2D space



dσ/dQ² Cross Section

Good shape agreement.





Systematics on π^{+-} -> π^0 Charge Exchange

- Background with π^{+-} -> π^0 looks very signal-like.

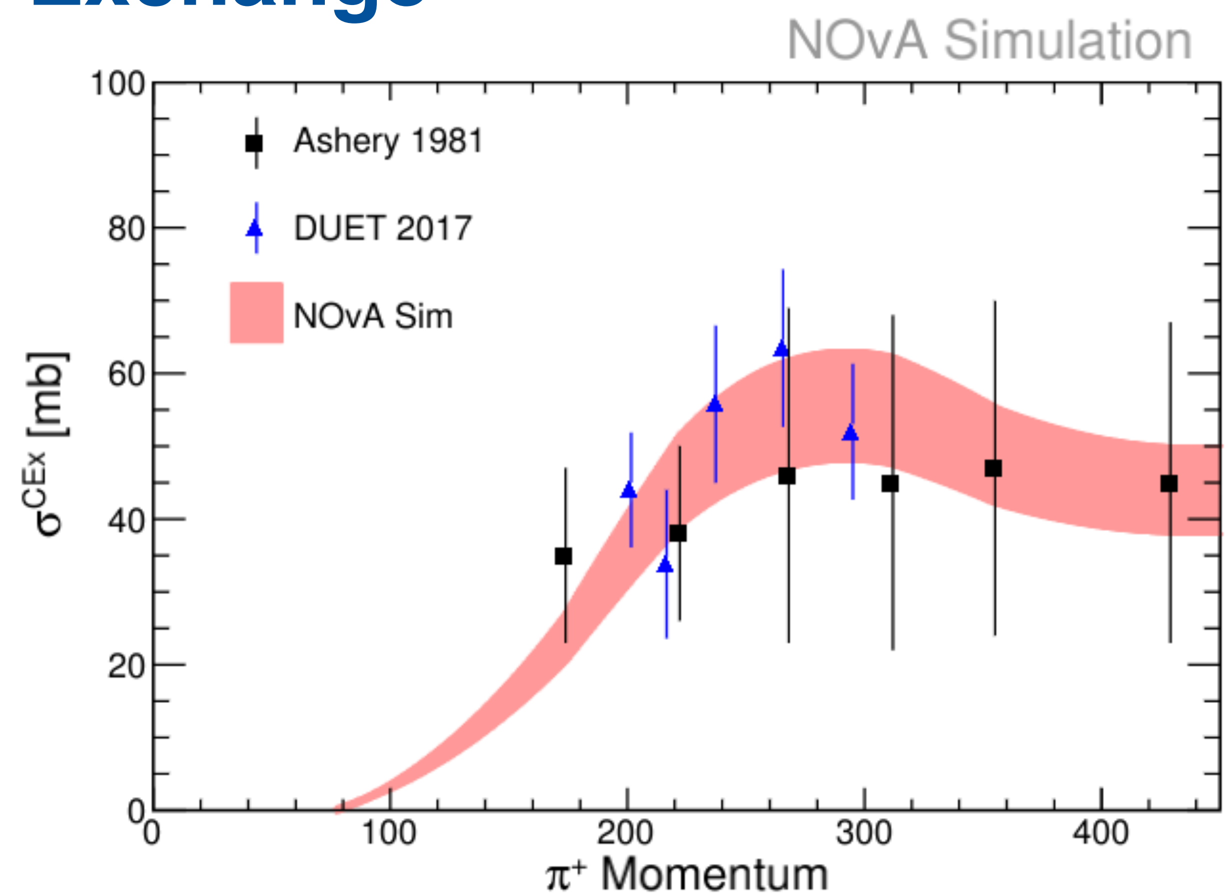
- Covariance fit of simulation to DUET 2017 results:

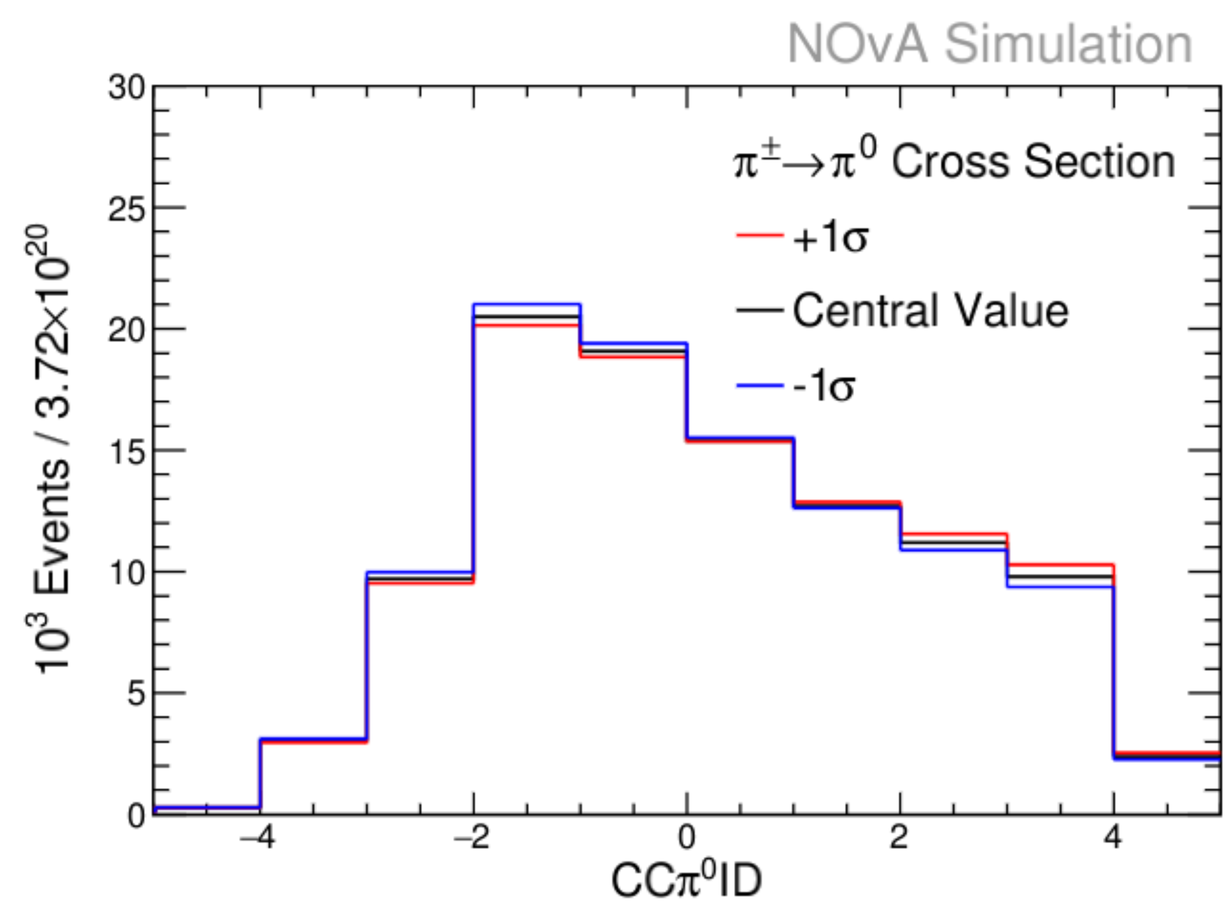
  Weight σ^{CX} to 1.061±0.146 of nominal value

  Phys. Rev. C 95, 045203 (2017)

- Noticeably skews CCπ0ID distribution for background

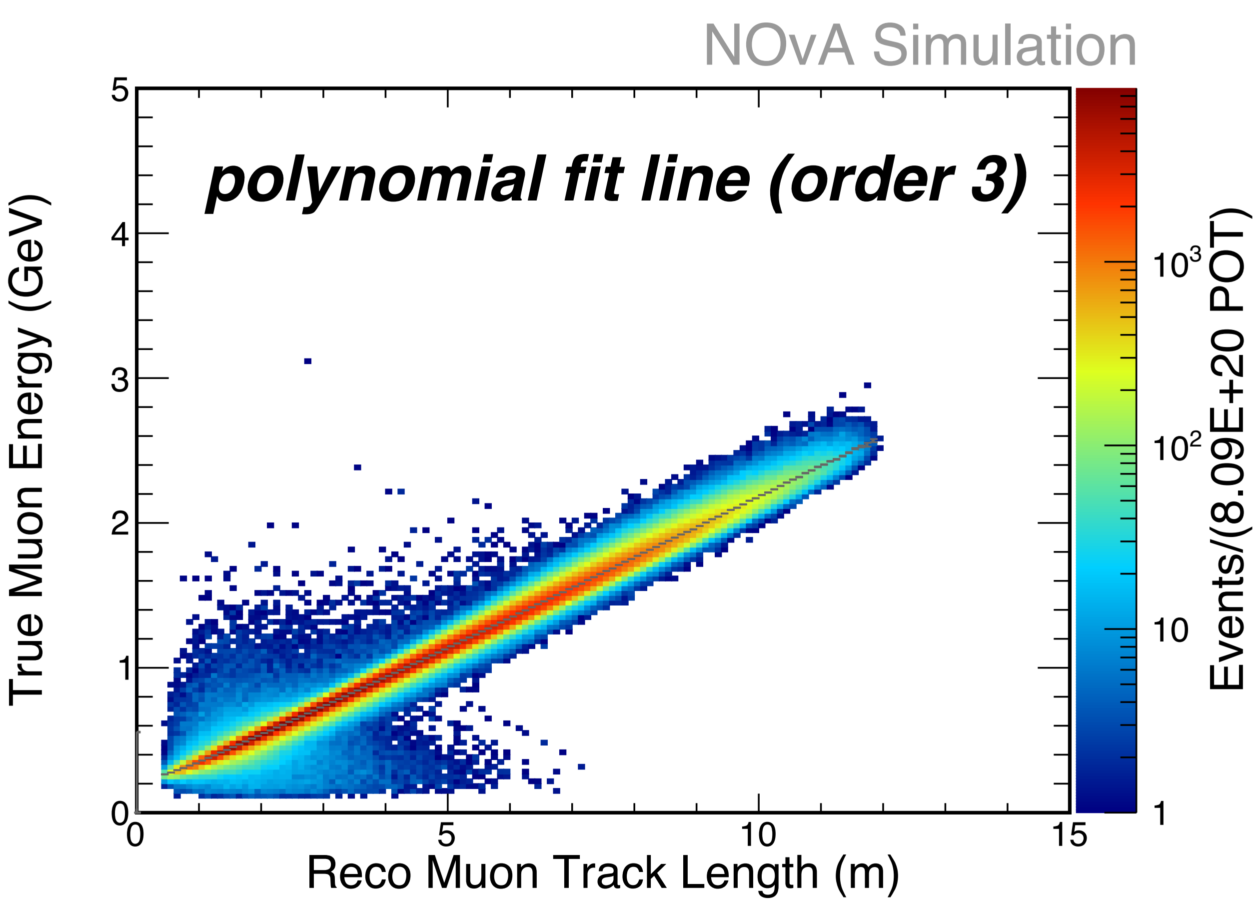
  4% impact on total cross section

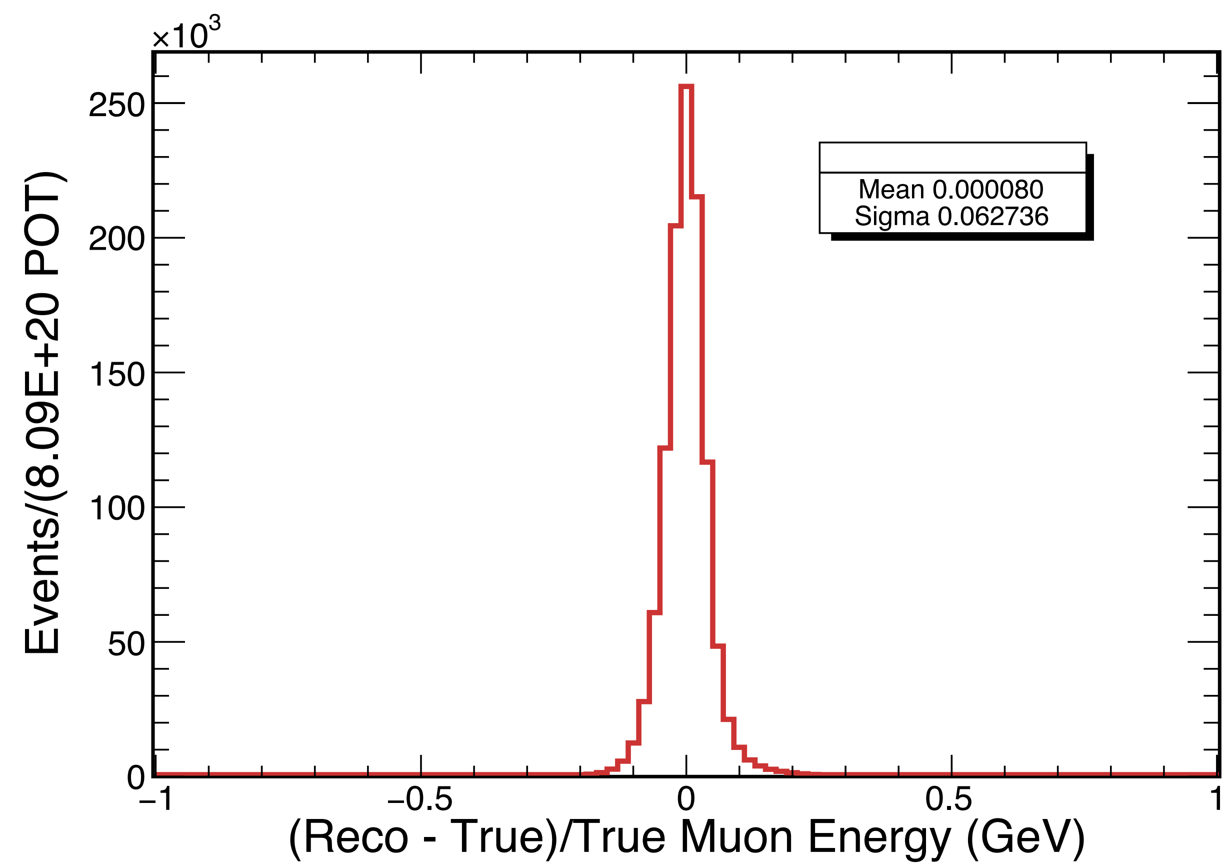




Muons in NuMu CC Inc

- Muon energy measured by range.
- Good muon energy resolution.





Event Selection on Pi+-

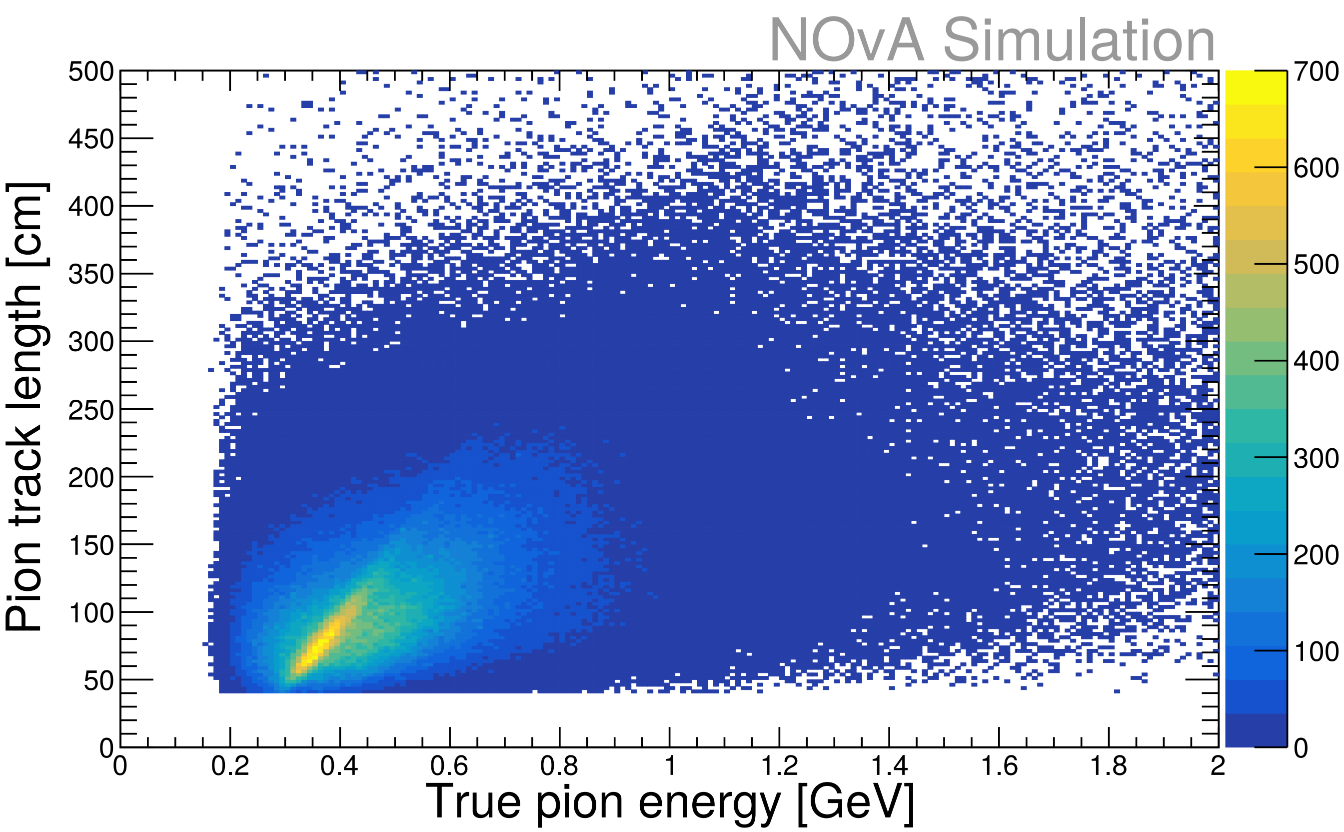
- Expected from MC:

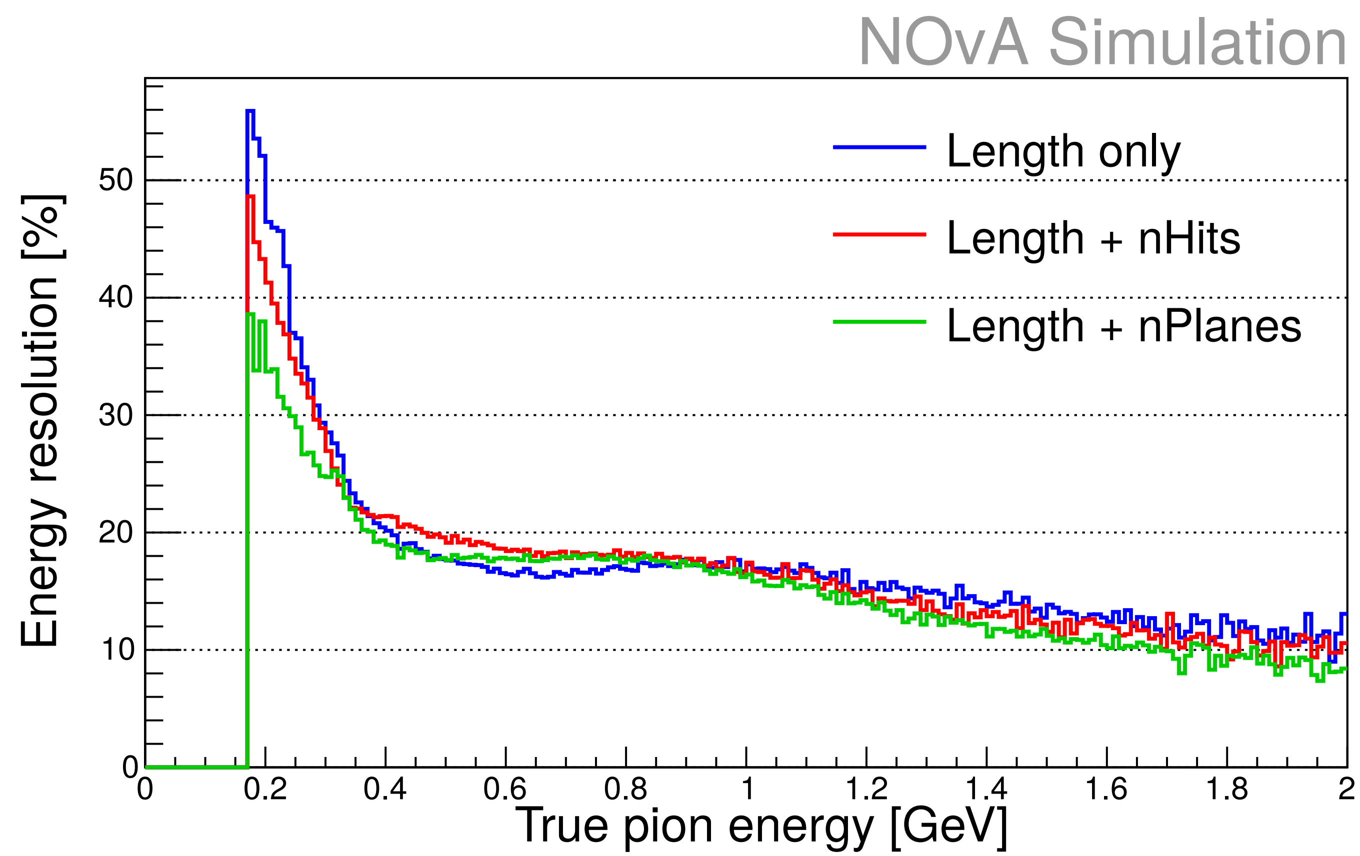
Cuts	Signal	Efficiency abs. (rel.)	Purity
ν_μ CC $\pi_{E\geq 350MeV}$	$2.74\ 10^6$	1.000 (1.000)	0.016
Quality	$2.74\ 10^6$	0.998 (0.998)	0.028
Containment	$3.38\ 10^5$	0.123 (0.123)	0.069
Fiducial	$3.19\ 10^5$	0.116 (0.944)	0.123
Muon ID	$2.14\ 10^5$	0.078 (0.670)	0.150
≥2 tracks	**$1.63\ 10^5$**	**0.059** (0.762)	**0.323**

- It allows for a systematics-limited cross-section measurement.

Pion reconstruction

- Use reconstructed information correlated with the pion energy, like the pion track length



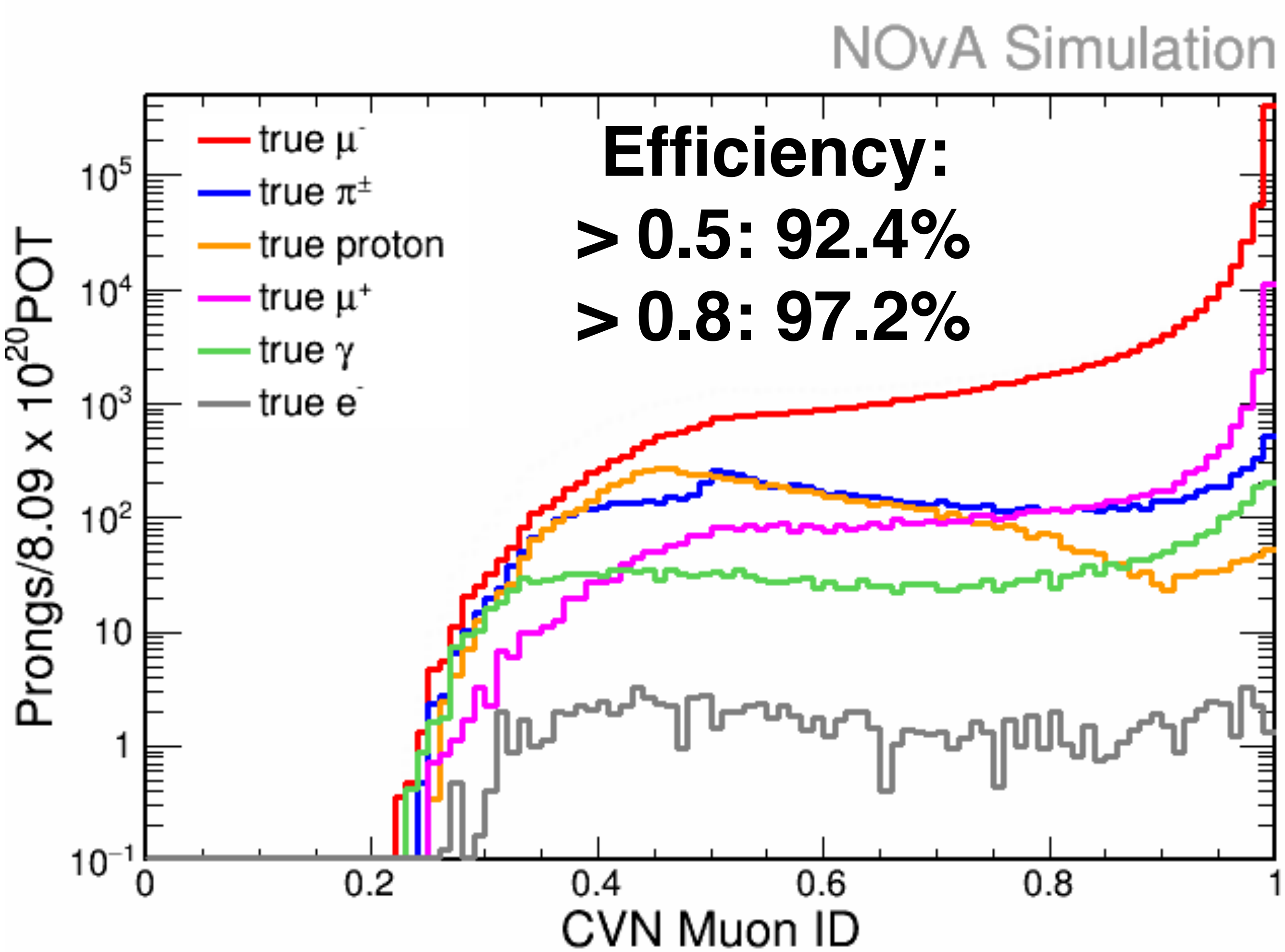


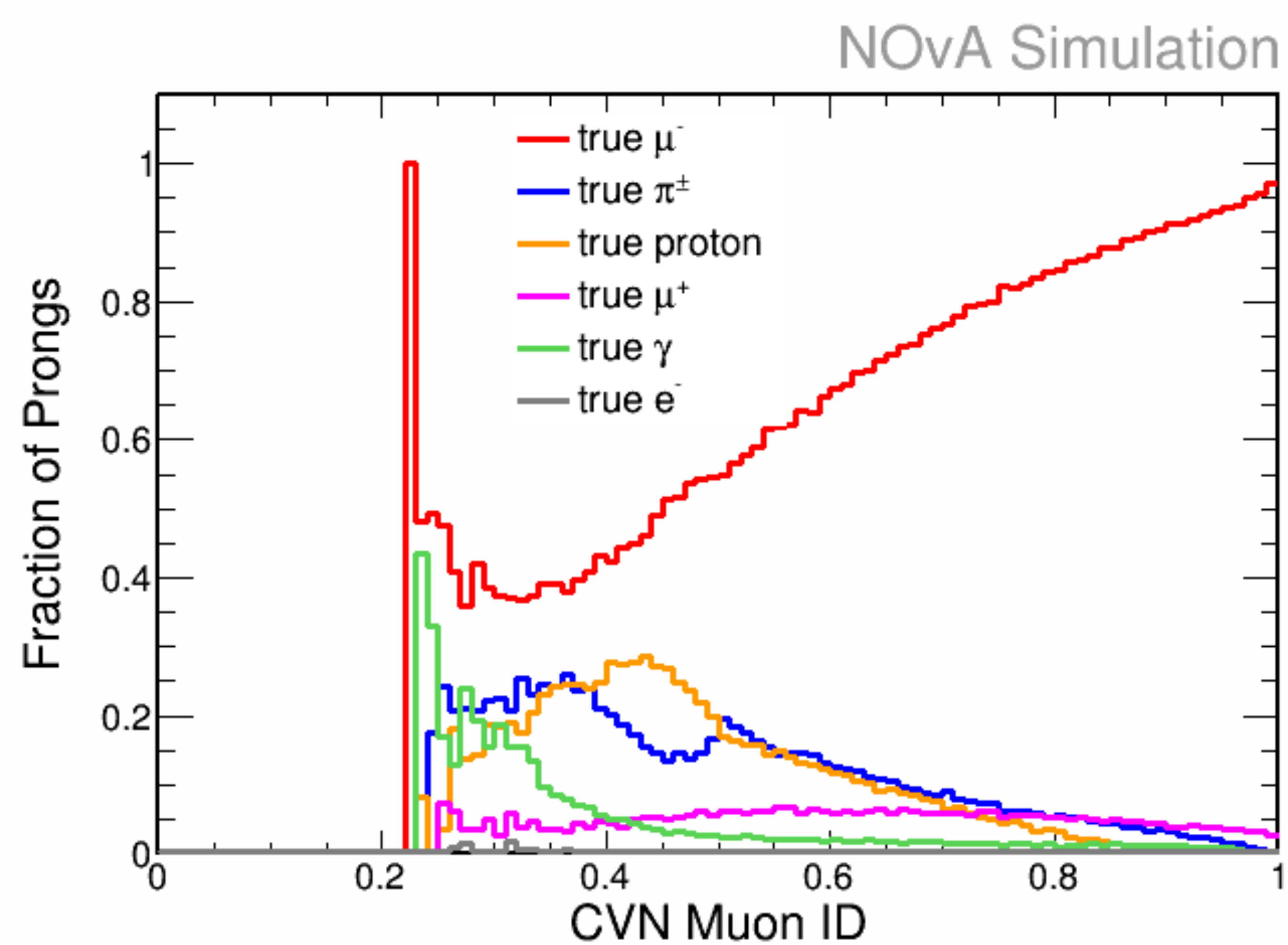
- Can achieve around 17% energy resolution.

Work in its first stages but expected progress this year.

CVN Performance for muons

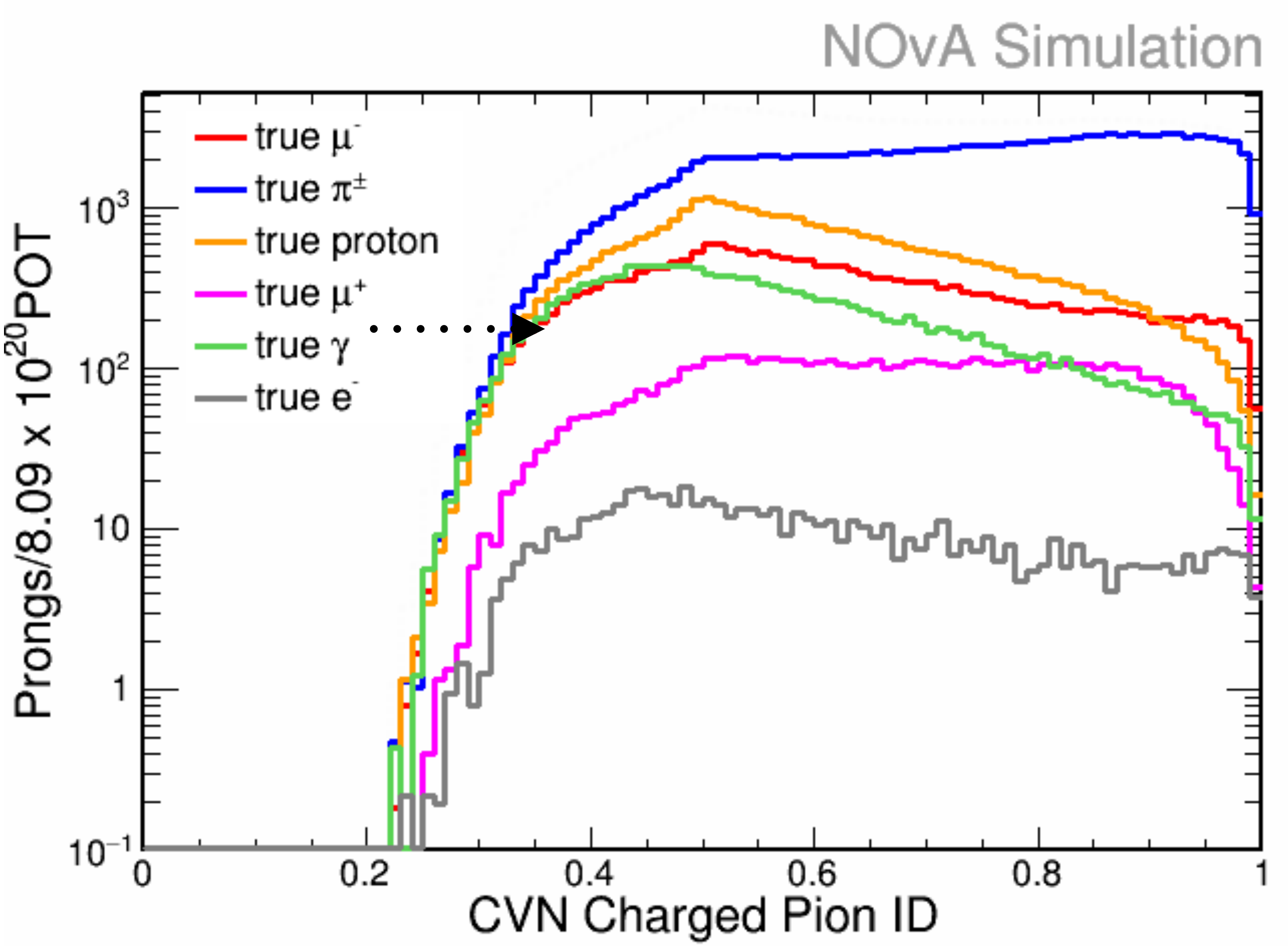
- Ratio to the total





CVN Performance Pions

Efficiency:
> 0.5: 61.6%
> 0.8: 67.0%



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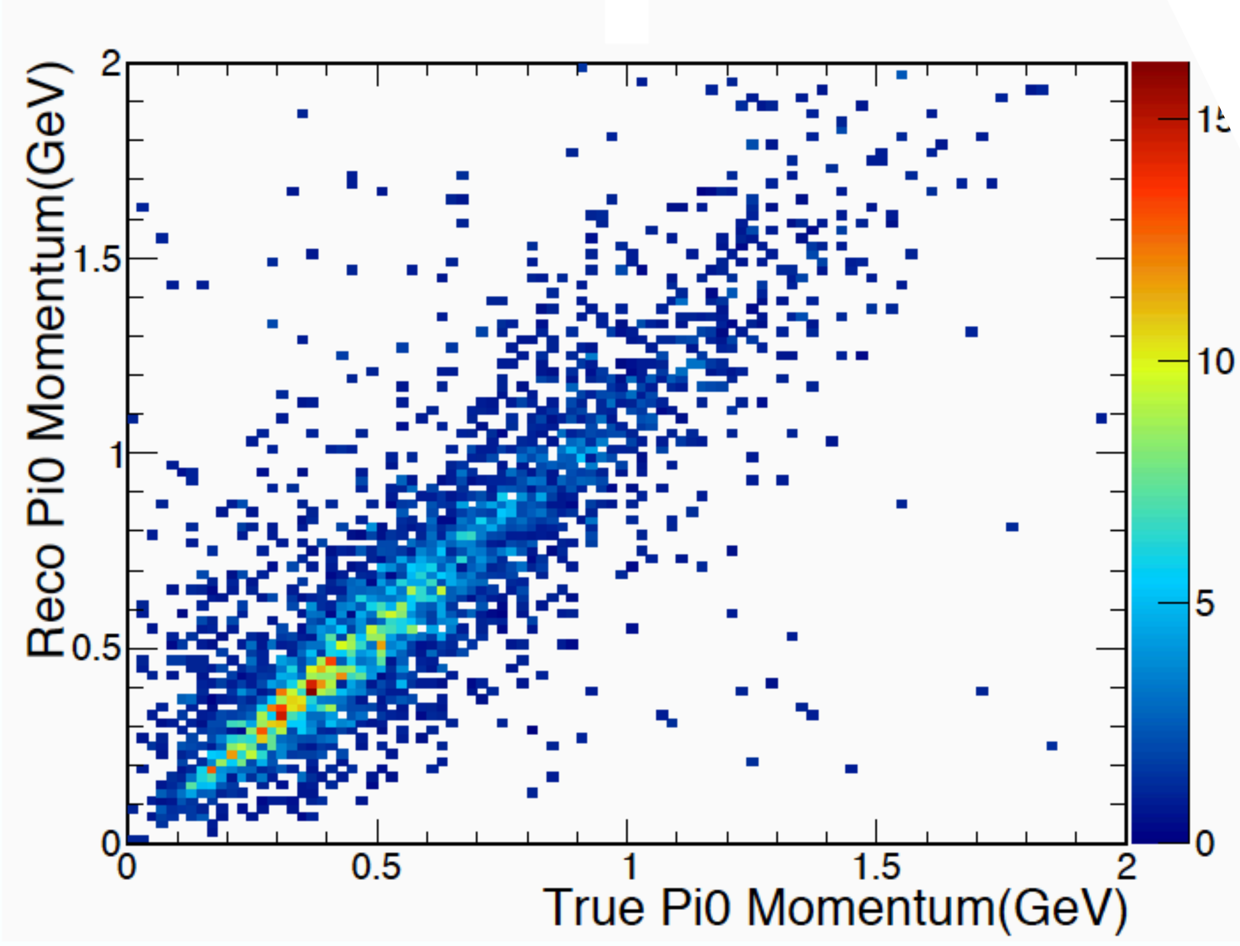
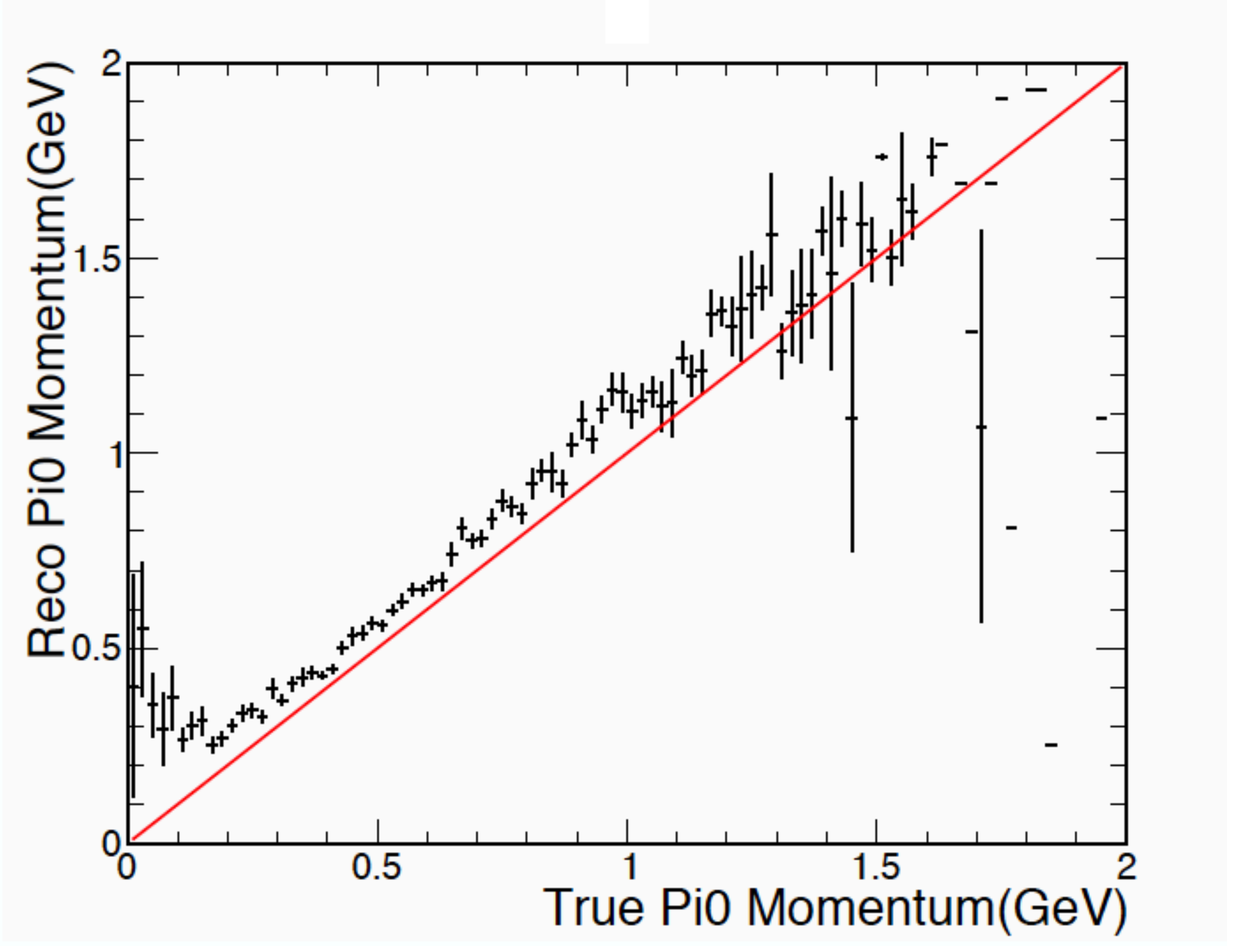
Reco vs. True Pi0 Momentum

- After m_{π^0} peak cut applied





Other analyses

- CC N π^{+-} (N>=1)
  - Working on improving π^{+}/π^{-} reconstruction.
  - Using prong-level CVN classifier for charged pions.
  - **The first goal is to report differential cross section in muon kinematics.**
- CC 0 π
  - **The first goal is to report differential cross section in muon kinematics.**
  - Working on improving the pion rejection.
  - Exploring proton reconstruction capabilities to study FSI.
- NC π^{0} (N>=1)
  - Important background to ν_e.
  - A event-level Boost Decision Tree (BDT) developed using shower variables as inputs.
  - **The first goal is to report differential cross section in π^{0} kinematics.**

Convolutional Visual Network (CVN)

One of our main challenges comes from identifying non-leptonic particles in the detector such as **protons** and **pions**.

- Currently, 2 times of training are actively used:

Prong-CVN: trained in prongs created in neutrino interactions